A STUDY OF THE EFFECTS OF SOIL COMPACTION ON PORE-SIZE DISTRIBUTION AND THE AVAILABILITY OF WATER TO PLANTS.

BY

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Volume "I" TEXT

TABLE OF CONTENTS

Volume "I"

EXPERIMENTAL

(All illustrations, figures and Appendix Tables are presented in volume II).

Summary

One pilot and three major experiments were carried out during 1971-1973 to investigate, in a clay loam soil, the effect of soil compaction on the availability, to plants, of the soil water through altering pore-size distribution. In the pilot experiment the suitability of the test crop, red clover, and the primary planning aspects of the major experiments were studied.

The reviewed literature indicated that compaction affects all soil-plant relationship factors (mechanical impedance, soil water, soil air, soil nutrient status and soil thermal properties) and that these factors interact with each other and with the metabolic processes of growing plants in a manner which make the study of the effect of compaction on any particular factor alone rather difficult. The isolation of the effect of compaction on the soil-water-plant relationship factor from the others was, therefore, essentially important. This isolation was approached by the use, in all experiments, of artificially compacted and non-compacted aggregates of specific, relatively small, size ranges instead of the whole soil. This approach was considered fruitful on the basis that within aggregate-porosity alterations are of major importance in the soil-water status, especially within the available range which is mainly concerned in this work, while playing a less important role in the other factors. The effect of compaction will, therefore, be more concentrated in soil-water status than in the other factors.

In order to subject plant growth to the differential water status of compacted and non-compacted aggregates, two watering regimes were used in experiments I and II: (1) continuous watering, whereby the ease of water movement within the soil towards the roots, was a major factor

(dynamic factor) in determining the availability of soil water for plants. (2) Discontinued watering at an arbitrary stage of growth, whereby plants in the later stage of growth, ending with wilting, depended on the retained water by the soil, hence the AWC of the soil (capacity factor) eventually played its role also in determining the availability of soil water for plants. In experiment III the two watering regimes were, imposing, in seven cycles of stress-applied, stress-released, tensions of 100 cm and 50 cm water, by means of a series of sand tanks especially constructed for this purpose, to the soil water in the pots, whereby the effect of the increased AWC of the soil by compaction on plant growth was exaggerated and the upper limit of AWC was controlled by applying tensions which are closely related to the actual field capacity of the soil.

In all the experiments, direct evaporation from the soil was minimized by mulching.

The results obtained and conclusions reached may be summarized as follows:

1. Compaction of the soil, a clay loam, results, when carried out at moisture contents near that of field capacity, in altering pore-size distribution towards an increase in the total volume of water-holding pores in unit weight of the soil but a decrease in the total porosity of the soil, with a resultant increase in the available water capacity of the soil but a decrease in its air capacity.
2. The experimental procedures were efficient in isolating the effect of compaction on soil-water from that on the other soil factors which are related to plant growth. The differential plant growth was, therefore, related mainly to the effect of compaction on soil-water status. The use of sand tanks and imposing stress in a

number of stress-applied, stress-released cycles were further successful approaches, both controlling and concentrating the effects on plant responses.

3. The alteration, by compaction towards an increase in the water holding pores in the soil, in addition to the increase in the AWC of the soil, enhances water movement in the soil at tensions within the available range, obviously resulting from an increase in the water conducting pores.

4. Both clover as a test crop and clay loam as the soil type contributed effectively in making this investigation a success.

5. Soil texture, through determining the consistency of the soil, and soil moisture content at the time of compaction, through determining the plasticity of the soil, play a major role in determining the degree of compaction achieved by a given force.

6. It is broadly postulated that the land-use system plays a big role in the "problem" of compaction.

7. Once a soil, with a high structural stability is over compacted cultivation practices do not improve the micro-structure of the soil.

8. Inasmuch as soil-water is concerned, if over-compaction is avoided, a degree of compaction could have beneficial consequences especially in areas where drought is a problem.

9. In areas where drought is not a serious problem, it is likely that levels of compaction regarded to give appreciable increases in the AWC of the soil will be accompanied by adverse effects on impedance, soil air, nutrient availability and thermal properties of the soil which could in some situations outweigh the benefits on the soil-water status.

REVIEW OF LITERATURE

COMPACTION AND OTHER FORMS OF SOIL DEFORMATION

Investigators in this field agree in principle on defining soil compaction as "the process of packing closer together the soil particles by an effective force exerted on the bulk of the soil which results in an increase in the soil's bulk density through a decrease in its total porosity" (Bruce, 1955; Li, 1956; Lull, 1959; Blake, 1963; Cooper and Gill, 1966; Gill and Vanden Berg, 1967, and Soane, 1970a).

To distinguish compaction from both consolidation and slumping, Soane (1970a) described the action of the applied force in compaction to be rapid and to cause no change in the soil's moisture content. Furthermore, Soane related the volume change in consolidation to a long-term overburden or static load, and in slumping to the loss of strength and soil movement resulting from the increase in the moisture content. Li (1956) was of the same opinion and related compaction to a dynamic load such as the blow of a hammer or passing of a vehicle. Puddling, according to Bodman and Rubin (1948) is another type of soil deformation in agricultural land caused by treading of stock or passage of vehicles under wet conditions which involves shearing of aggregates by tangential stresses in addition to the compaction by normal (vertical) stresses. Under very wet soil conditions such stresses result in plastic flow in which no increase in bulk density occurs (Marshall, 1959). The term compression is also used, especially in engineering texts, synonymously to compaction. However, compression denotes the decrease in the voids ratio per increment of applied load or pressure (Baver et al, 1972). Raney et al (1955) considered the term compaction as "general" and pointed out the importance, in research work, of distinguishing genetically-developed from traffic-induced compacted layers. In the former, the compacted layer has been developed through slow but long continued action of soil genetic processes. Claypans and fragipans are examples of this type. In the latter, it has resulted from recently applied forces such as implement traffic or trampling upon a soil that had, under virgin conditions, physical properties favourable to the plant growth. From the mechanism point of view, soil compaction is considered by Gill and Vanden Berg (1967) as a dynamic soil behaviour which represents compression failure. They defined compression failure in soil as the state of stress at incipient volume change.

The process of compaction and its amount depend on the strength resistance of the soil against the stress produced by the acting force. When the stress produced by the acting force is higher, compaction takes place which in turn results in a progressive increase in the strength resistance of the soil till equilibrium is reached and settlement is achieved, at which point the degree of compaction is at maximum for the particular force and soil conditions (Li, 1956; Lull, 1959; Gill and Vanden Berg, 1967; and Soane, 1970a). Thus the complex of compaction is the result of interacting factors of soil properties and force characteristics.

Soil Factors

Soil Consistency

In a glossary of soil science terms by Soil Science Society of America (1970) the consistency of a material is defined as its resistance to deformation and rupture, and Baver *et al* (1972) stated that the concept of soil consistency includes such properties of the soil as resistance to compaction and shear. Baver (1930) pointed out the possibility of predicting the values of the dynamic properties of any plastic soil from the consistency forms. The limits of these forms, according to Archer (in press) are indicators of points of change in the strength properties of the soil. The minimum strength resistance of a soil which allows the maximum compaction to be achieved by a given force has been found by Baver (1930) to exist when the consistency of the soil is in the plastic range (Fig. 1). Similar relationships were found by Proctor (1933) and Weaver and Jamison (1951). This was explained by Baver et al (1972) to be due to the ease of orientation of the particles at this stage. Baver (1930) demonstrated that the maximum compactability of a soil is a logarithmic function of the plasticity

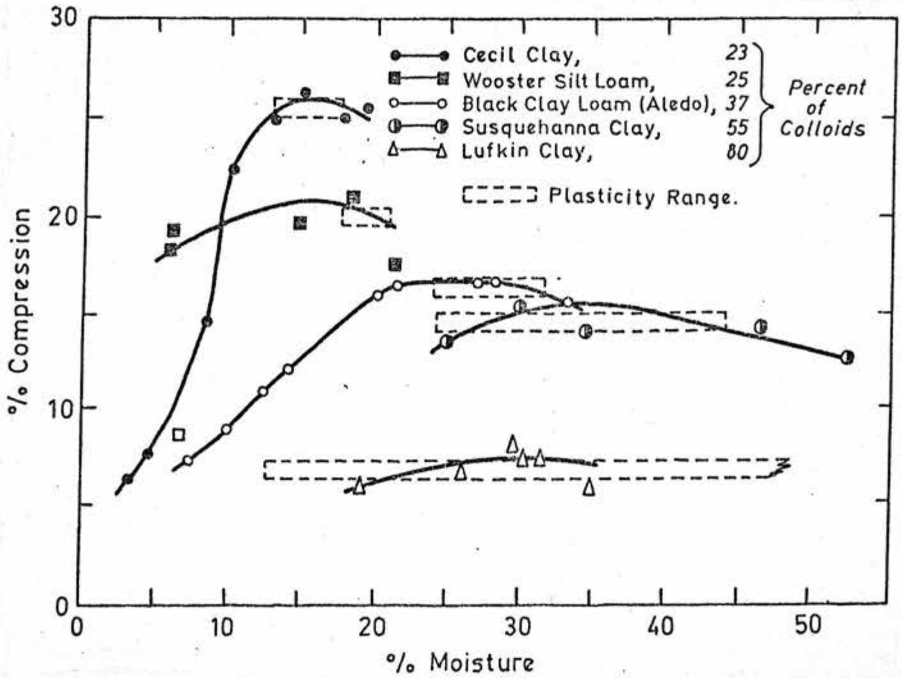

Fig. 1. The percent compaction of soils of various textures at different moisture contents and their relation to the plasticity range. (After Baver, 1930).

number (Fig. 1). Gill and Reeves (1957) found a high correlation between the compactability index and log plasticity number. They computed the compactability index as the slope of the curve obtained by plotting bulk density versus log applied force at moisture contents approximating wilting point.

The different forms of consistence of a soil are the result of both molecular attraction (cohesion) and surface tension (adhesion) forces. The magnitude of these forces depend on some properties of the soil and its moisture content. The major soil properties which affect its consistency, and hence are involved in its behaviour towards compaction, are the percent of clay and the organic matter content. The effects of other factors such as the type of clay, chemical composition, particle size distribution and the structure of the soil have also been reported to have some effect (Marshall, 1964; Gill and Vanden Berg, 1967; Kohnke, 1968, and Baver et al, 1972).

Clay Content

Baver et al (1972) has stated that soils of low clay contents are characterized by smaller plasticity numbers and lower moisture contents at the lower plastic limit (Figs. 1 and 2,b), and demonstrated that the plasticity number is a linear function of the clay content, and Odell et al, (1960) found a high correlation between the clay content and the Atterberg limits. The role of the clay content in determining the consistency of the soil is related to its high specific area. Li (1956) stated that one percent of clay in a sand contributes more than 90 percent of the total surface area. Li presented evidence to demonstrate the important role of the clay fraction in the soil in the compaction process.

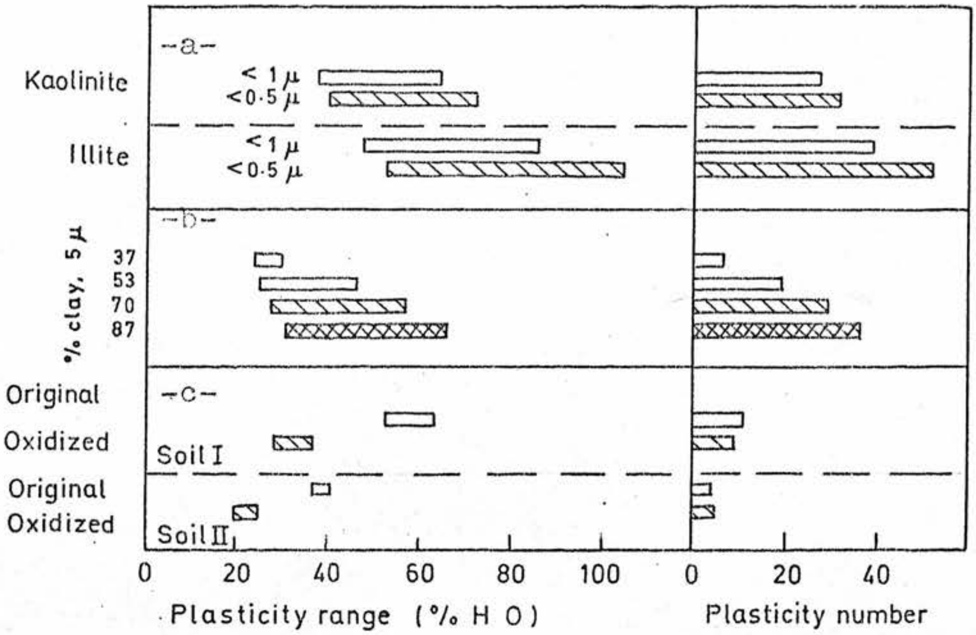

Fig. 2. - Factors affecting the Atterberg consistency constants. (After Baver et al, 1972).

The effect of the type of clay on the consistency of the soil (Fig. 2,a) is related to the differences in the total surface area of the particles. Farrar and Coleman (1967) found a difference in the level of significance when they correlated the total and the external surface areas of nineteen British clay soils with their liquid limits, plastic limits, cation exchange capacities and clay contents. According to Marshall (1964), in montmorillonite, due to the uptake of water internally, both the upper and lower limits are higher than in kaolinite, but the plasticity number is about the same for a given particle size of the two types. Dumbleton and West (1966) however, concluded that the type of clay affects the plasticity number also.

The nature of the exchangeable cations according to Baver (1928) has a considerable influence upon soil plasticity. This influence is through the effects of ionic hydration on the thickness of water films and the space which accommodates the ions (Marshall, 1964). However, these effects, according to Baver et al (1972) differ between the expanding-lattice type clays and those that have a rigid crystalline structure. Sowers (1965) has even recommended the use of distilled water in the determination of Atterberg constants to avoid the change in the results which can be significant because of the ions present in many public water supplies.

Organic Matter Content

Russell (1971) was of the opinion that the problem of soil compaction would be made easier of solution if the humus content of the soils could be maintained at a fairly high level. The structure deterioration of the soil in modern agriculture is related by Klute and Jacob (1949) to the replacement of the horse by the tractor in tillage operations. The former not only caused little compaction, but also was a source of considerable amounts of manure. Marshall (1959) stated that the presence of organic matter slows down wetting and thus increases the stability of the soil. The data of an experiment by Gerard et al (1962) indicate that the rate of moisture loss from a fine sandy loam influences the degree of its compactness. Ermich (1957) has reported reduced compaction as a result of improved tilth created by the addition of organic matter. From an experiment on the influence of organic matter additives on some soil physical properties, Taylor and Henderson (1959) demonstrated the effectiveness of various sources of organic matter on reducing the compactability of the soil. Morgan et al (1966) compared the compactability of unamended soil with soils amended with peat, lignified redwood and calcined clay and found that the compactability of the soils was in the order: unamended > peat > lignified redwood > calcined clay. Russell et al (1952) reported that twenty five annual applications of farmyard manure at rates of 0, 10, 20 and 40 tons per acre resulted in highly significant differences in the susceptibility to compaction of a silt loam. Free et al (1947) noticed that soils containing higher amounts of organic matter were compacted to a lesser degree by a given compactive effort at a given moisture content and that the moisture contents at which maximum compaction occurred, which they found to be close to the lower plastic limits, were higher (Fig. 3). Odell et al (1960) found a close relationship between the organic carbon and the Atterberg limits. Baver (1930) found that oxidation of the organic matter (Fig. 2,c) resulted in a marked lowering of both the upper and lower plastic limits and a slight tendency towards a decrease in the plasticity number.

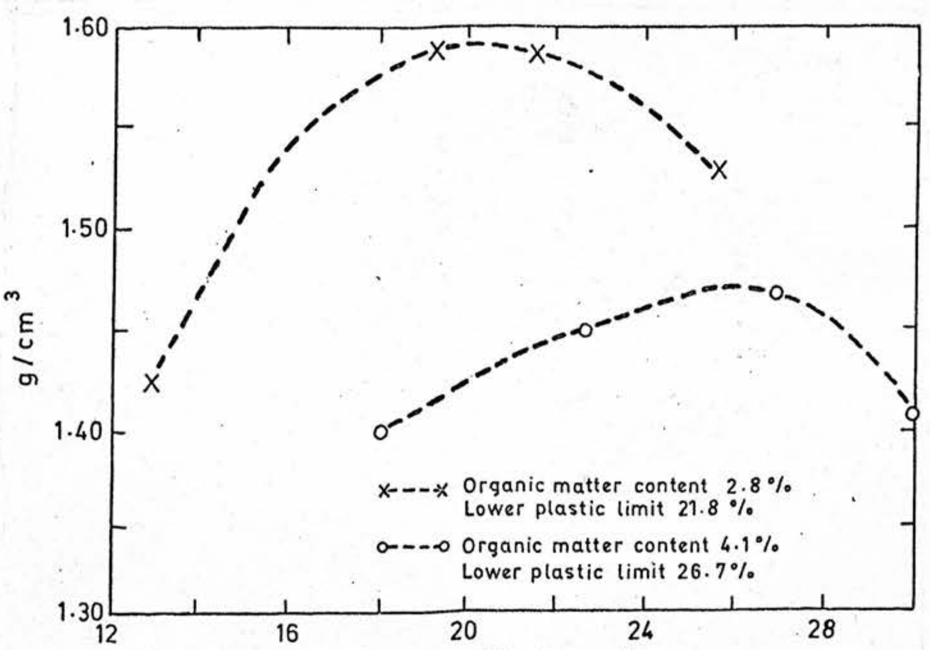

Fig. 3. Compaction-moisture content curves of a Honeoye silt loam at two organic matter content levels. (After Free et al, 1947).

Particle-size Distribution

In addition to the role of the texture of the soil in the determination of its consistency, and hence its dynamic properties, the role of the particle-size distribution, from a geometrical point of view, is of great importance in determining the bulk density of the soil through packing. Soane (1969) stated that due to the narrow range of the variation in the particle densities of different soils compared with the wide range of their apparent densities, the differences in maximum bulk density cannot be attributed to differences in particle density but to the facility for interstitial packing. Harris (1971) stated that the particle size distribution is the factor which characterizes the manner of packing, and the manner of packing is the controlling factor in the response behaviour of the soil to an external load. Marshall (1959) presented curves of compacting soils of various particle-size distributions by Proctor's 1933 method (Fig. 4). Similar curves on the relationship between soil texture and bulk density have been obtained by Weaver and Jamison (1951).

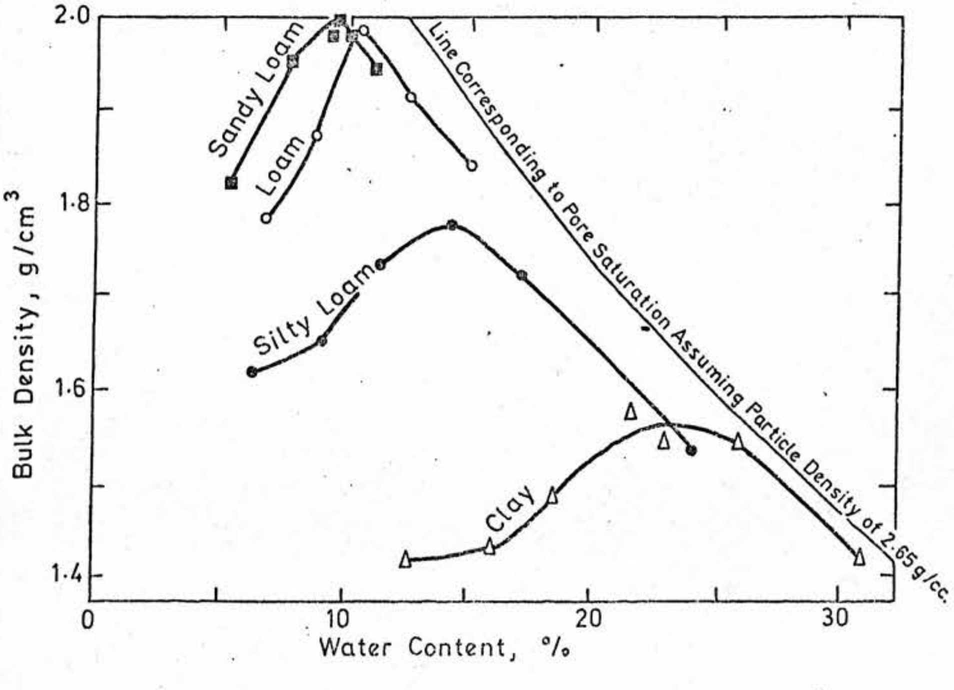

Fig.4. Compaction of soils of different textures. (After Marshall, 1959)

Soil Structure

In the definitions of soil structure by Jongerius (1958), Brewer and Sleeman (1960), Marshall (1962) and Russell (1971) emphasis is on the arrangement of soil particles and of the pore space between them. Therefore, soil compaction by definition, could be considered as a structural change, and the degree of compaction as a structural property of the soil. According to Gill and Vanden Berg (1967) soil structure together with the integrated influence of the material properties of the soil determine the specific active and passive behaviour of the soil when subjected to an acting force system. They described the active behaviour of the soil as a specific action in which the soil matrix moves, as in compaction, and the passive behaviour as the one in which the soil matrix participates without movement as in the case of air movement within the soil body. Gill and Vanden Berg furthermore, stated that when the force acts, i.e. compaction takes place, the structure is changed, and as a result both the active and passive behaviour are altered, in other words the role of structure in the complex is in both directions. On the other hand, the influence of the material properties is in one direction as they are not altered by the action of the force. Resistance to compaction is suggested by Richards et al (1960) to be used as an index for the evaluation of structural status of soils. Though one of the dominant factors determining the compactability of a soil is its degree of compaction at the time the force acts on it (Free et al, 1947 and Lull, 1959), the resistance to compaction, according to Cooper and Nichols (1959) depends on the coefficient of internal friction and the structure of the soil. Soane (1969) stated that aggregates, because of their high internal density, irregular shape and considerable internal strength, tend to resist compaction. The stability of the aggregates is one of the factors which affect the persistence of a particular geometry against deforming forces (Marshall, 1962) and soils having exceptionally stable aggregates are highly resistant to destruction either by tillage or natural processes (Martin et al, 1955), hence, impart to the soil physical properties which do not change as a result of management. Lambe (1962) showed the influence of applying different rates of aggregants on the compactability of a sandy clay (Fig. 5). Ermich (1957) noticed, from compaction curves, the beneficial effects of increased structural stability by treatment with synthetic conditioners. From field experimental results, Uehera et al (1962) concluded that as a result of the comparatively stable structure of Hawaiian Latosols, the use of heavy mechanized equipment has not perceptibly altered the

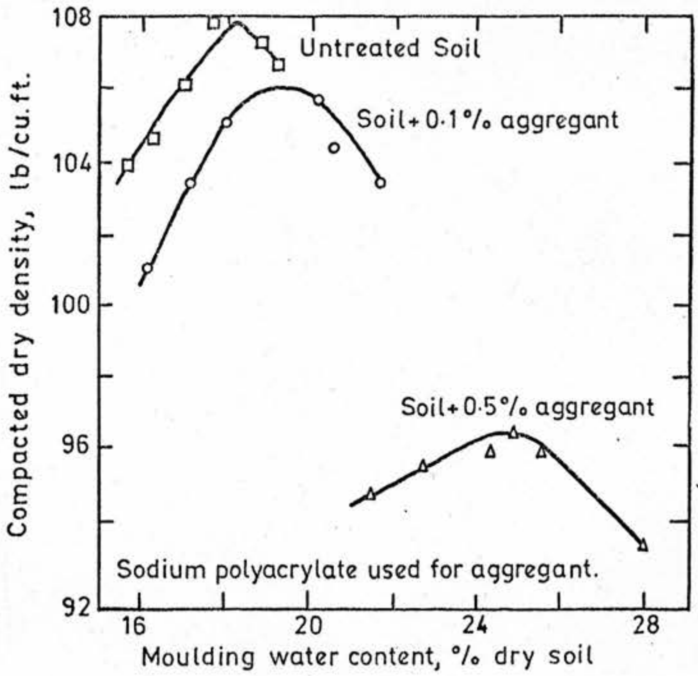

Fig. 5. Aggregants influence on the compactability of a Virginia sandy clay (After Lambe, 1962).

physical properties of the soil. The stabilization of structural pores, which involves a mechanism for holding soil particles against the action of water and traffic, is one of the fundamental problems in soil structure management (Russell, 1971).

Moisture Content

In the 1970 report of the Agricultural Advisory Council on soil structure and soil fertility titled "Modern Farming and the Soil", it is stated that "soil consistency describes the changes which water brings about, through the forces of cohesion and adhesion, in the nature and physical properties of soils which have an important influence on the timing of cultivations, the bearing strength of soils and the structural changes brought about by pressures and stresses". Slipher (1932) considered the effectiveness of tillage in the structure-making process to be delicate and highly sensitive in its relations to the soil moisture content. Vomocil et al (1958) postulated that though force characteristics alterations, such as decreasing the load and reducing the number of passes, decrease compaction, yet their effects are small compared with the changes caused by alterations in the soil moisture content at the time of the force action. According to Reney and Edminster (1961) best possibilities of prevention of compaction are in more careful attention to the soil moisture content at time of tillage.

The effect, at low levels, of moisture content of the soil on its degree of compaction by a given force involves the action of thin films of water surrounding the particles as lubricant which allows for a closer arrangement by the action of the force and hence a high bulk density (Soane, 1970,a). In dry soils, the resistance of the particles to rearrangement is greater because, as Lull (1959) stated, there is no lubrication and also the surface tension is pronounced. At high moisture contents, because the pores are full of water, which in its liquid phase is uncompressable, close packing is restricted (Marshall, 1959). The moisture content-compaction relationship of cohesive soils is illustrated by a characteristic curve (Foster, 1962) as shown in Fig. 6. The moisture content of the soil at the peak of the curve, i.e. when maximum compaction by a given force occurs, is termed the "optimum moisture content for compaction". In cohesionless soils, the optimum moisture content is that of saturation (Li, 1956). In cohesive soils, which are mainly concerned in agriculture, and hence, are only dealt with herein, the optimum moisture content tends to be within that of the plastic range. Bruce (1955) reported that the optimum moisture content occurs midway between the 1/3 and 15 bar suctions irrespective of the past cropping history of the soil. Mazurak and Chesnin (1964)

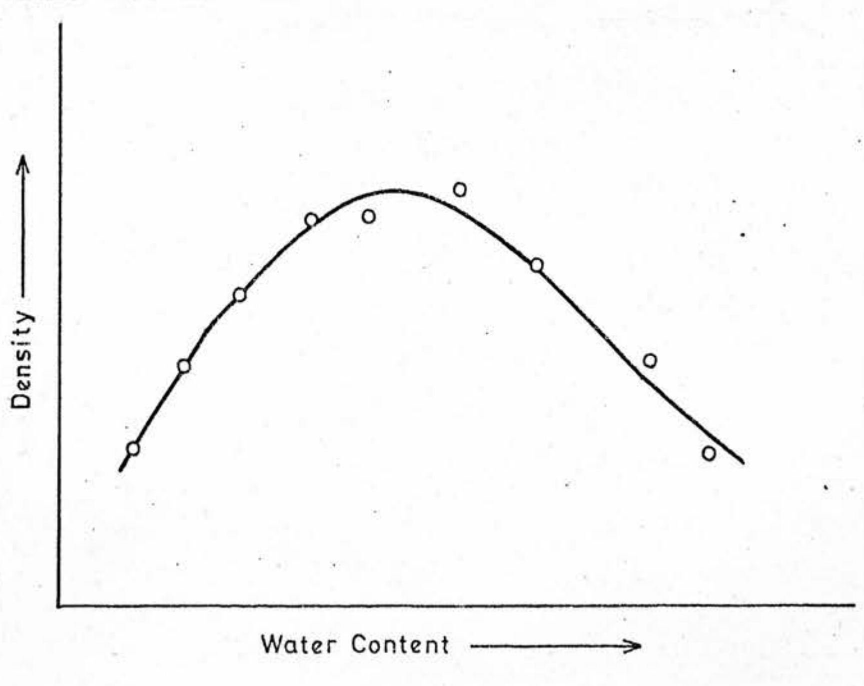

Fig. 6. Typical compaction curve for cohesive soils (After Foster, 1962).

using Proctor method for compacting a slightly plastic sandy loam, found that optimum moisture content was that of 1/3 bar suction which was very close to the lower plastic limit. Vomocil et al (1958) reported the optimum moisture content of the Yolo fine sandy loam to be within the plasticity range but closer to the lower plastic limit. Weaver and Jamison (1951) using both Davidson loam and Cecil clay in studying the relationships between the moisture content of the two soils and three levels of compaction energy, concluded that the peak tendencies occurred in vicinity of the lower plastic limit. The results of their experiment (Fig. 7) also showed that with high compaction energies, higher maximum bulk densities are obtained but the

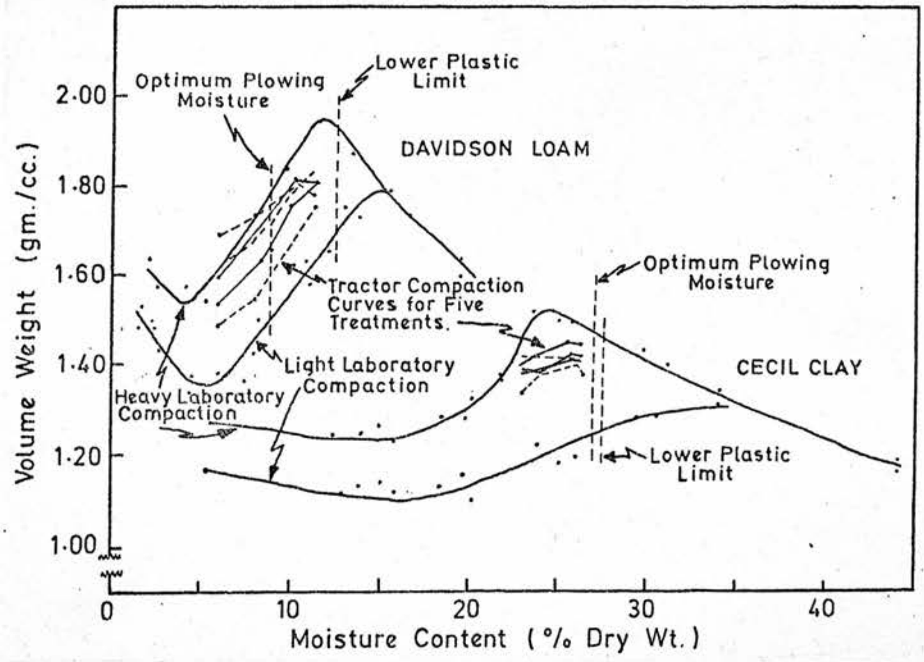

Fig. 7. Compaction-moisture content relationships of Davidson loam and Cecil clay for laboratory and tractor compaction studies. (After Weaver and Jamison, 1951).

optimum moisture contents tended to be lower than the lower plastic limits. These results suggest that the optimum moisture content for compaction does not depend only on those properties of the soil which determine its consistency, but also on the compaction energy. Li (1956) stated that for any soil type the compactive effort must carefully be considered when the optimum moisture content for compaction is determined. The relationship between the compactive effort and the optimum moisture content for compaction will be dealt with under the force factors.

Force Factors

A precise description of the role of force factors in the compaction complex has been considered as "difficult" by a number of workers (Joint ASAE and SSSA soil compaction committee report, 1955; Nichols and Reaves, 1955; Cooper and Nichols, 1959; Gill and Vanden Berg, 1967 and Soane, 1970,b). In the description, as stated by Cooper and Nichols (1959), the measurement of the force alone, gives no indication of the resultant compaction unless all the involved factors of the soil are considered. The variability of the reaction of the soil factors to the force is the major cause of the complexity. The following are among the soil factors, given by Gill and Vanden Berg (1967), which give rise to such complexities especially in the field:

1. The mass of the soil to which the force is applied is usually a three dimensional semi-infinite medium where the applied force is distributed over a small section of the surface. Hence, the concept of force per unit area becomes meaningless as neither direction nor a finite area is fixed.

2. The concept of the state of stress at a point, which describes forces within a medium, cannot be precisely applied due to the fact that the soil is a porous granular material.

3. Both the action of the force and the reaction of the soil, i.e. its behaviour, are involved, and if the behaviour is changed, as in the case of soil strength during the action of the force, the effect of the change should be included in any quantitative description of the complex.

In a symposium on soil compaction of the American Society of Agricultural Engineering (1961) it is pointed out that none of the available theories of stress-strain relationship accurately coincides with the observed phenomena in the soil. Nichols and Reaves (1955) were of the opinion that the analysis of the force applied by tillage implements on the soil is further complicated by the curvature of the surface applying the force which may approach the soil at various angles. Soane (1970,b) included the variability of the shape and size of loaded area among the factors which affect the distribution of the force under the wheels of agricultural implements and result in a more difficult complex.

It is generally accepted that the dynamic load of implements is the most common cause of compaction in agricultural land. Therefore, it will be the only type which is dealt with herein. The complexities of the dynamic load, due to both motion and time factors, are even more difficult than those of the static load to describe. Nevertheless, its role in the compaction complex is known to involve, in general, the following factors:

1. The intensity of the pressure.

2. Surface distribution of the pressure, and the ground contact area.

3. The distribution of the pressure within the body of the soil.

<u>The intensity of the pressure</u>

As the amount of the force increases, the resultant compaction tends to be higher, and maximum compaction is reached at a lower optimum moisture value (Weaver and Jamison, 1951). The line which connects the optimum moisture contents for a type of load at different intensities is termed the "line of optimums". The slope of the line of optimums, (Foster, 1962), which follows the general shape of the zero air void curve, (Fig. 8,a) is a characteristic of the type of the load (Fig. 8,b).

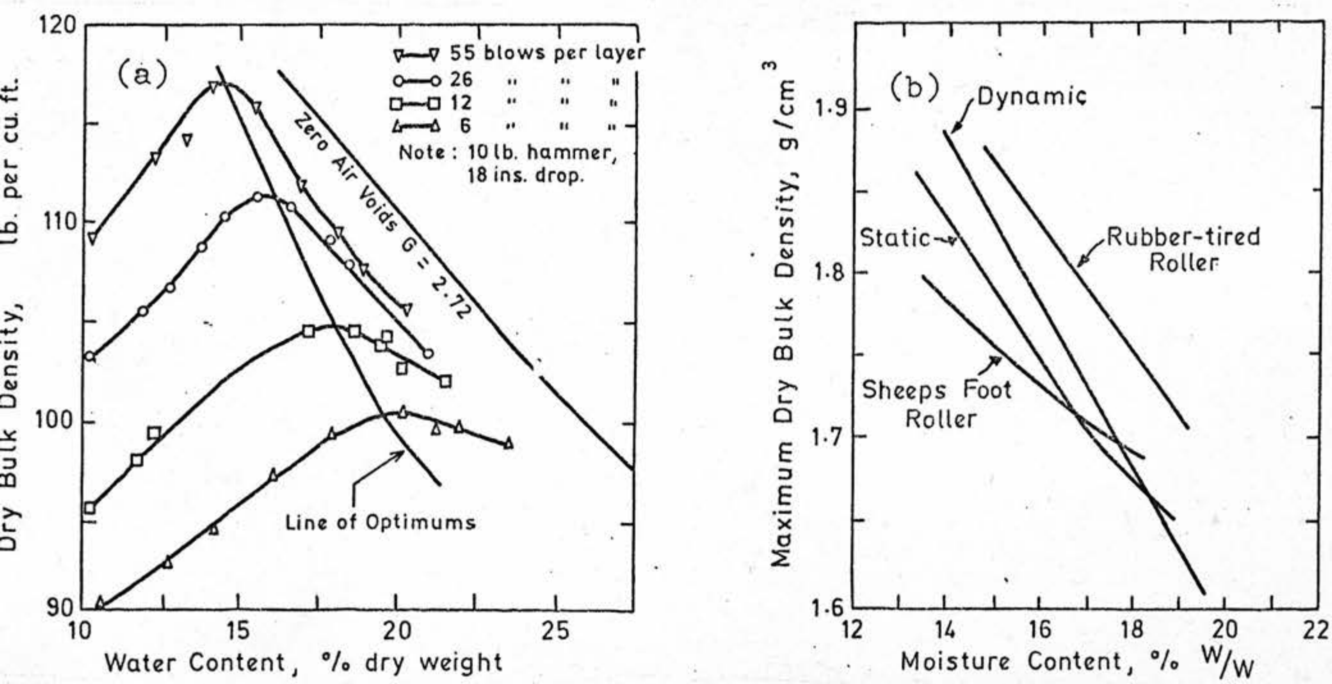

Fig. 8. a) A typical line of optimums. b) Lines of optimums of different types of loads. (After Foster, 1962).

Under dynamic loads, the intensity of the force, in addition to the weight, depends on both the speed of the implement, which determines the duration of the action of the load in one pass, and the number of passes. Vomocil et al (1958) noted a decrease in the amount of compaction when the speed of the tractor was increased. Attwood (1953) studied the effect of changing the speed of a roller on the degree of compaction and concluded that 1 m.p.h. resulted in maximum compaction, and that increasing the speed above 1 m.p.h. caused a markedly less compaction up to approximately the speed of 3 m.p.h., after which the effect of increasing the speed was very little. Attwood attributed the insignificant differences in the amount of compaction at different high speeds to the bouncing effects. However, he did not study the effect of speeds less than 1 m.p.h., but extrapolated to zero speed from his results. This extrapolation was later criticised (Fountain and Paine, 1953) and the conclusion that 1 m.p.h. is the most effective speed was considered unjustified.. Aboaba (1966) concluded that low compaction at high speeds is due to the time factor. Li (1956) stated that the amount of compaction depends upon the intensity rather than upon the weight of the load, and that the intensity of a dynamic load, i.e. energy input, is a direct function of the speed. Slipher (1932) was of the opinion that the amount and vigour of tillage should be carefully adjusted to the exact resistance of the soil type.

The 1971 report of the Agricultural Advisory Council entitled "Modern Farming and the Soil" states that "studies should continue into advising multiple operations which have the effect of reducing the number of passes over the land". Though it is generally accepted that the greater the number of passes over an area, the greater is the amount of compaction, there is evidence that the first few passes cause most of the compaction. In engineering works, where maximum compaction is the aim, experiments have shown that for a given roller and type of soil, the maximum density is achieved by a definite number of passes, beyond which the energy is only wasted (Lewis, 1954 and Li, 1956). The data of an experiment by Weaver and Jamison (1951) on the changes in the effect of compactive effort by varying the drawbar load or the number of passes, show that the greatest increase in bulk density occurred during the first four of ten passes by a tractor tyre. Lull (1959) presented the results of an experiment by Steinbrenner (1955) on the effect of repeated tyre passes on bulk density of the soil which show that the first three passes resulted in most of the compaction. Nevertheless, Raney and Adminster (1961) were of the opinion that increasing the weight of the implement by having more tools on it as an attempt to reduce the number of passes could actually increase the compactive effort, and that such consequences should be realised and considerations should be given to the energy input rather than just the weight of the implement or the number of passes.

Vibration is another factor which increases the intensity of pressure by dynamic loads. Lewis and Parsons (1961) showed that, with vibration, the number of passes required to achieve maximum compaction by a roller, is approximately halved. The effect of vibration on noncohesive soils is found to be much greater than on cohesive soils (Lewis, 1954). Cooper and Nichols (1959) stated that though an even clay is compacted to a moderate extent by intense vibration, the effect on clay is far less conspicuous than on sand, because the cohesive bonds between clay particles interfere with inter-granular slippage.

In agricultural works, especially in experiments on soil structure and bulk density, vibration has been used to achieve close packing of small quantities of confined soil. Rosenberg (1959) used a "vibration probe", which was a commercial concrete vibrator, inserted in the centre of the soil column and operated till the desired bulk density was obtained. In 1960, Rosenberg used a vibrating table, on which the pots were fixed, filled with soil and an aluminium plate was placed on the top of the soil. The system was then operated, and, when necessary, extra weight was placed on the aluminium plates, till the desired bulk density was achieved. With both methods, Rosenberg reported satisfactory results of both the achievement of desirable and comparable bulk densities and the elimination of the disadvantages of pressure and tramping such as lack of vertical uniformity and breakdown of aggregates.

Surface Distribution of Pressure and Contact Area

Though the total pressure produced by a load on the soil is a direct function of its weight, duration and presence of vibration, the magnitude of the transmission of this pressure into the body of the soil, which is of great importance in the resultant compaction, is characterised by the dimensions of its contact area with the ground, and hence, its distribution. Bekker (1961) stated that the dimensions of contact area have a great significance in the compaction complex, and presented the following equation on load-contact area-sinkage relationships:

$$P = (k_c/b + k_o)\ z^n$$

where P is the pressure on the soil, k_c is the cohesive component which is a function of the size of contact area, b is the smallest dimension of contact area, k_o is the frictional component which is independent of the size of contact area, z is the depth of sinkage which is an indicator of the amount of compaction and n is a constant which expresses the soil characteristics. However, according to Soane (1970,b) due to some difficulties in computing the size, shape and pattern of contact area, the calculation of surface distribution of pressure is far from simple. Nevertheless, the mean pressure per unit area is generally accepted and used by a number of workers in this field (Vanden Berg et al, 1957; Soehne, 1958 and Reaves and Cooper, 1960). The factors which make the size, shape and pattern of contact area difficult to compute include the motion action of the implement, the degree of sinkage, the inflation pressure and the type and dimensions of the tyre. Gill and Vanden Berg (1967) stated that dynamically and statically loaded areas are considerably different. Soane (1970,b) related the difference between the effects of a static and a moving wheel to the bulldozing action in front of the moving wheel and to some recovery in the soil after the wheel has passed. The degree of sinkage, which for a given load depends on the soil strength, markedly affects the size and pattern of contact area (Bekker, 1961). Soehne (1958) illustrated (Fig. 9) the relationships between soil strength, degree of sinkage and the size of contact area. Fig. 9 also shows the effect of the presence of lugs in the tyre on the way the contact area develops as soil strength decreases and degree of sinkage increases. Trabbis et al (1959) used tranducers to measure the distribution of pressure "in front, underside, back and on the carcass between the lugs" along the width of a lugged tyre at inflation pressures of 10, 14 and 18 p.s.i. They noted that the distribution is not uniform, and that higher values tend to be towards the centre of the tyre. Their results also showed that higher values were associated with high inflation pressures which resulted in smaller sizes of contact area.

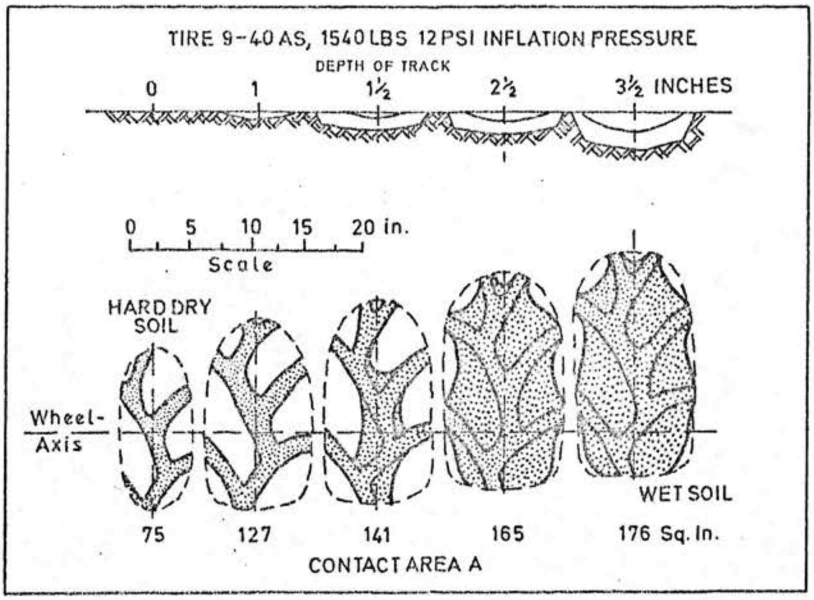

Fig. 9. Contact areas and degree of sinkage of a tyre under different soil strengths. (After Soehne, 1958).

The distribution of pressure under smooth rubber tyres has been studied by Vanden Berg and Gill (1962) by embedding pressure cells in both the soil and the carcass of the tyre, and running the tyre over firm and soft soils under inflation pressures of 6, 10 and 14 p.s.i. They demonstrated (Fig.10a) that low inflation pressures resulted in larger contact areas, hence, lower pressure per unit area than in the case of high inflation pressures. They also noticed that the strength of the soil considerably affected the pattern of distribution (Fig.10b), and that the general pattern of the distribution was different from that of lugged tyres as the high values did not occur in the centre but in a zone surrounding the central region of the tyre. Cohron (1971) considered low inflation pressure and flexibility of farm tractor tyres as measures of control on external forces to minimize soil compaction.

In Sweden, as reported by Soane (1970,b) the farmers are advised to use lower inflation pressures for the rear tyres when the tractor is used in the field than those recommended for travel on roads.

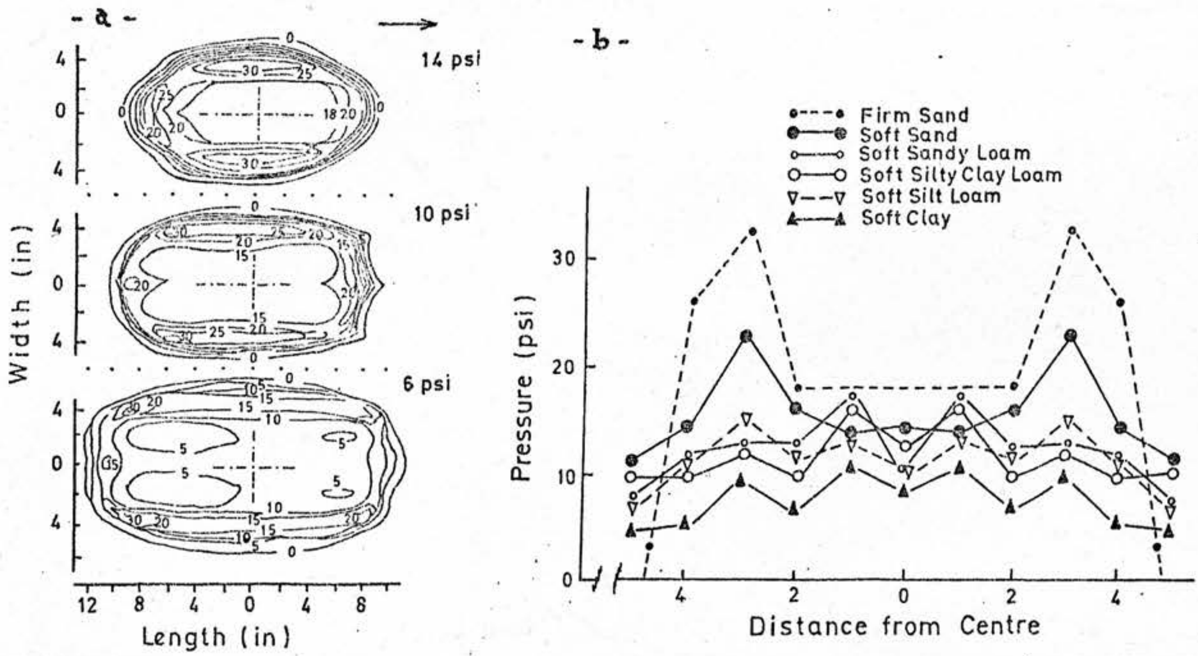

Fig. 10. a) Pressure distribution under 11-38 smooth tyre on a firm sand at inflation pressures of 6, 10 and 14 p.s.i.

b) Lateral pressure distribution of the same tyre at 14 p.s.i. inflation pressure in six different soil conditions.
(After Vanden Berg and Gill, 1962).

Vanden Berg and Gill (1962) stated that there is a significant interaction between the type of tyre and soil conditions. Below tracks, the contact area is not as variable as below wheels. The only causes of the variability being the shape and roughness of the ground surface especially under conditions of high soil strength (Soane, 1970,b). The mean pressure per unit area under the track is found to be considerably less than that under the wheel (Lull, 1959). Reaves and Cooper (1960) compared the pressure distribution under a 12 in. track and a 13-38 tractor tyre (Fig. 13) at 16 p.s.i. inflation pressure both carrying the same dynamic load and pulling the same drawbar. They found that intensity of pressure distribution under the tyre is at least twice as much as under the track. However, the contact area of the track, due to its large dimensions, was several times more than that of the tyre.

The dimensions of the wheel or the track are the main factors in determining the size of contact area. Soane (1970,b) stated that surface pressure of a given load can be decreased by increasing the diameter or width of the tyre. Furthermore, there is evidence that for tyres having the same contact area, the narrow tyre with large diameter will sink less than a wider tyre with smaller diameter (Lull, 1959). Bekker (1956) as quoted by Cohron (1971), has shown that a long narrow contact area of a load reduces the overall compaction and confines the compaction to a smaller area. However, the diameter to width ratio of the wheel is an important factor to be considered in the design of the agricultural implements, as it involves performance, economy and efficiency (Gill and Vanden Berg, 1967).

Pressure Distribution within the Soil.

In the previous section, the factors which determine the size of contact area and the pattern of surface distribution of the force were considered. Though there is evidence showing the effect of the size of contact area on the magnitude of stress distribution within the soil, the literature contains no clear reference on the effect of the pattern of the surface distribution of the force on its distribution within the soil. Sowers and Sowers (1951) stated that when a load is applied to a soil surface the vertical stress through the soil is concentrated directly under the loaded area and extends indefinitely in all directions, and that near the surface the distribution depends on the size of contact area, but at depths greater than about twice the width of the loaded area the distribution is practically independent of the way the load is applied. Below such depths and beyond the slope of 45^{o} from the edge of contact area, the stress boundary, according to Bekker (1961), is of no importance for practical purposes. Soehne (1958) stated that the amount of concentration of compactive stresses around the axis of load depends on factors of soil strength such as moisture content, cohesion and density. For mathematical computation of stress distributions in the soil modified forms* of Boussinesq's formulae are developed to solve agricultural problems (Barber, 1965). The modifications were necessary because Boussinesq's formulae are applicable to stress measurements at a point in a point-loaded, homogeneous, elastic, isotropic material and all of these conditions are rarely found in any agricultural field. According to Soehne (1958) the modifications were made by Froehlich (1934) by introducing to these formulae a "concentration factor" (v) which must be obtained experiment-

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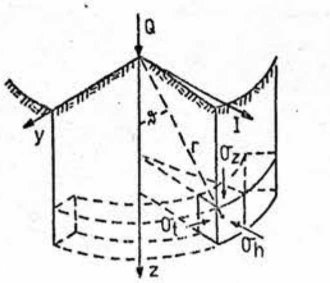
* A modified form of Boussinesq's formula is:

$$\sigma z = \frac{vQ}{2\pi z^2} \cos\theta^{\ v+2}$$

where σz is the perpendicular compressive stress, v is the concentration factor and the other symbols are demonstrated in the diagram which illustrates Boussinesq's formula.



VERTICAL COMPRESIVE STRESS

$$\sigma_z = \frac{3Q}{2\pi r^2} \cos^3 \psi$$

ally for soils at different degrees of strength.

By assigning v values of 4, 5 and 6 for high, medium and low conditions of soil strength respectively, Soehne (1958) calculated the state of stress at different points in soils under different strength conditions and types of load, and traced the pressure isobars to illustrate (Fig. 11) the role of soil and force factors in determining the patterns of stress distributions in the soil. In the calculations, however, Soehne had assumed an even surface distribution of the pressure and obtained the whole field of pressure by superposition of stresses from single point loads. This assumption was criticised by Gill and Vanden Berg (1967). They were of the opinion that the problems of isotropy

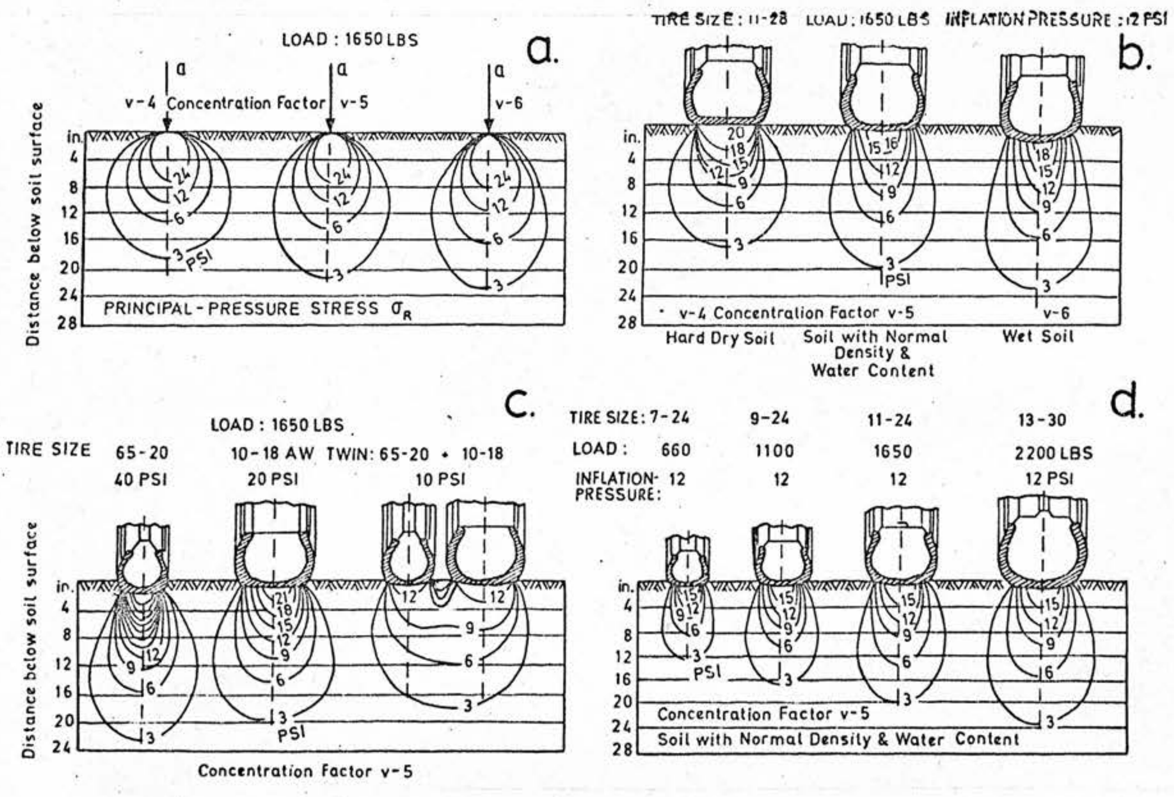


Fig. 11. Stress isobars under: (a) a point load at different concentration factors- (b) a tractor tyre for different soil conditions- (c) narrow, wide and twin trailer tyres at different inflation pressures, and (d) under different tractor tyres. (After Soehne, 1958).

and stress-strain linearity are too complicated to be solved by such formulae, and that v values, although they modify the general shape of distribution, do not in fact represent measured soil parameters of true physical significance. Nevertheless, the general patterns of distribution so determined, are reported by Terzaghi and Peck (1967) to correspond, to a reasonable extent, with those measured directly. Vanden Berg et al (1957) measured the pressure distributions under the front and rear wheels of a tractor in a sandy loam from a number of pressure cells embedded at different depths in the soil, (Fig. 12). Reaves and

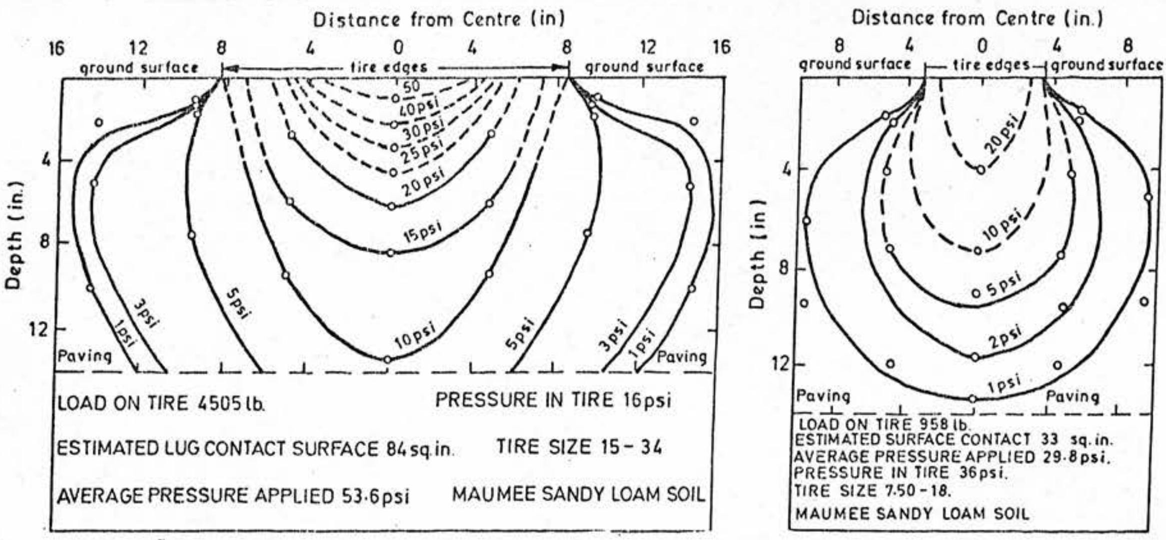


Fig. 12. Iso-pressure lines under (a) the front and (b) the rear tractor wheel in a dense soil. (After Vanden Berg et al 1957).

Cooper (1960) used similar techniques to measure and compare the distribution of pressure under a track and a tyre differing in the size of contact area, but carrying the same dynamic load and pulling the same drawbar (Fig. 13).

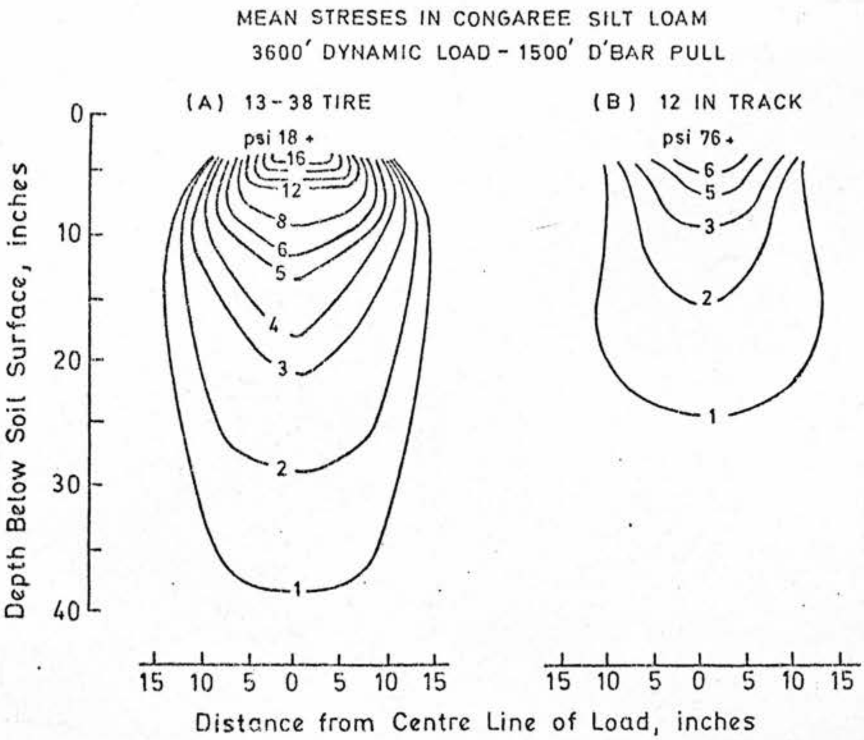


Fig. 13. Stress distribution isobars perpendicular to the direction of travel for equally loaded tyre and a track. (After Reaves and Cooper, 1960).

The use of pressure cells is criticised (Freitag, 1971) for the disturbance the soil receives when the cells are embedded, especially in the vicinity of their locations where the natural continuity of the soil is affected, and for the fact that they respond to the normal component of the stress vector and not to the shearing stresses, a problem which becomes more complicated when large deformations occur in the soil and the cells rotate.

The patterns of pressure distribution within the soil is measured, indirectly, by the determination of location and degree of the resultant compaction by the action of the force. The direct means for this approach is measurement of the bulk density at different points before and after the action of the force. Measurements of bulk density within the soil down to the affected depths have been carried out by Soane (1968) by using gamma-ray transmission equipment developed at the Scottish Station of the National Institute of Agricultural Engineering. Some of Soane's results are presented in Fig. 14.

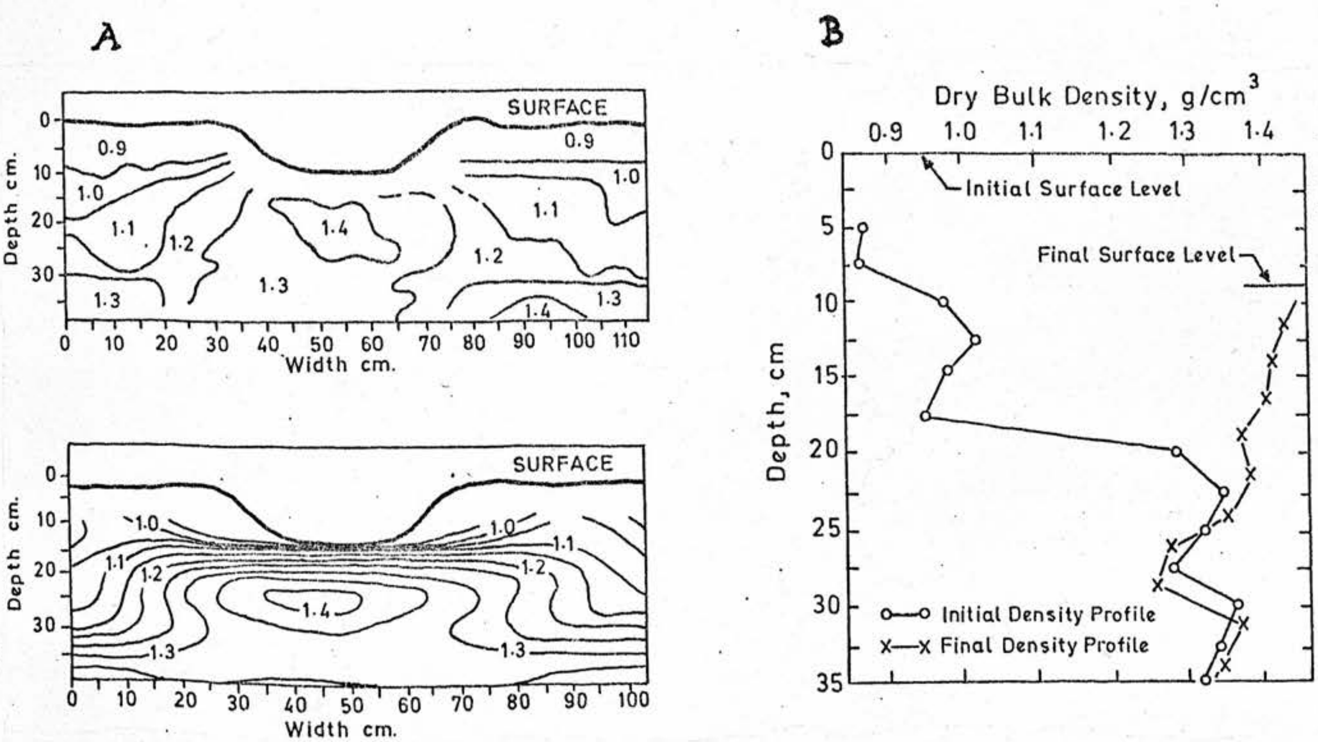


Fig. 14. A- The distribution of dry bulk density after passage of a tractor wheel with isodens inserted (above) by eye and (below) by trend surface analysis.

B- The variation of dry bulk density with depth before and after the passage of a tractor wheel. (After Soane, 1968).

COMPACTION MEASUREMENTS

When a soil is compacted, three of its properties undergo changes, these are: total porosity, pore-size distribution and soil fabric (Freitag, 1971). Compaction also alters soil strength (Warkentin, 1971). The study of the magnitude of the change in these properties is the basis for numerous methods available for compaction measurements. These properties of the soil are also factors of great importance in various soil-plant relationships, and the experimenter usually measures the property which serves as means of assessing the agronomic effect of compaction which is under investigation.

The measurement, as much as the nature of the procedure allows, is carried out either whilst the process of compaction is in progress, or by comparing data obtained "before" and "after" the action of the force (Soane, 1970,a).

Total Porosity

The total porosity of the soil is calculated from the absolute density of its particles, for which the pycnometer method (Blake, 1965) is standard and its bulk density, using the following formula:

$$\text{total porosity} = 1 - \left(\frac{\text{bulk density}}{\text{specific gravity}}\right) \times 100$$

The measurement of bulk density is carried out either from representative samples or directly *in situ* at locations of investigation.

Representative samples method

In this method bulk density is calculated from the dry weight of the sample, i.e. after oven-drying to a constant weight at $105^{\circ}C$, and its volume of natural field structure, for which the following methods are available:

1. Core method: Metal cylinders of known internal volume fitted in a special device by which it is pressed into the soil. The cylinder and the soil core are removed and the core trimmed level to the ends of the cylinder before oven-drying.
2. Pit method: The surface of the soil is exposed and levelled, then a loose sample of the soil is excavated by the aid of a spoon and placed in a container for oven drying. The volume of the pit, which is equal to that of the excavated soil, is then determined by a simple method, such as filling the pit with sand of known density or pouring a mixture of plaster of paris and water in it and measuring the volume of the produced cast of plaster of paris by displacement.
3. Clod coating method: Clods are taken from the field and coated in paraffin wax, vinylite resin or rubber solution and their volume determined by displacement. The oven-dried weight of the soil is then obtained by breaking open the clod and taking a sample for moisture content determination.

However, the determination of the volume of the sample is rather complicated by two sources of problems, these are:

1. Swelling and shrinkage of soils with changes in its moisture content gives rise to difficulties in deciding whether to determine the volume when the soil is dry or moist. According to Vomocil (1965) workers in the fields of plant growth and soil water movement prefer to make the determination when the soil is at field moisture content.
2. The above mentioned methods of sampling and volume determination of the samples are associated with some difficulties which may

cause variabilities in the results, such as:

(i) In the core method, hammering and vibrating the sampler might cause soil compaction under moist conditions or loosening under dry and hard conditions. In both cases, the density of the soil in the sampler varies from the actual bulk density of the soil (Zwarich and Shaykewich, (1969). Furthermore, the method is not practically applicable in uncoherent soils and soils of stony and gravelly natures (Vomocil, 1957).

(ii) In the pit method, the main source of error in the results is in the way the volume of the excavated hole is determined. The means of such determinations such as the rubber balloon, the sand-funnel and the cast of plaster of paris, have been criticised for their accuracy by Blake (1965), Zwarich and Shaykewich (1969) and Freitag (1971). Nevertheless, the method does not involve the risk of compaction and shattering and it is suitable for use on all soils including those of a stony nature.

(iii) In the clod coating method, the ability of the coating material to seal against entry of the immersion liquid, the amount of its penetration into the pores of the clods and the correction for its volume are the major sources of error (Russell and Balcerek, 1944). Other claimed disadvantages of the method include the difficulties associated with the moisture content determination of the sample and the fact that the measured volume is that of the clod and not of the bulk of the soil.

Other common disadvantages of the representative samples method include the disturbance of the soil they cause especially when sub-soil measurements are required (Blake, 1965), being tedious and not suitable for measuring the bulk density of thin horizons (Soane, 1970,a) and since separate samples must be used for the "before" and "after" data, statistically reliable comparisons require a large number of measurements (Freitag, 1971).

In Situ Methods

Measurement of bulk density of the soil *in situ* is carried out directly by detecting the magnitude of interaction between certain electromagnetic rays and the mass per unit volume of the soil, and using the obtained data as indicators of bulk density.

Watson and Jeffries (1949) suggested the X ray diffraction method, which is based on measuring quartz concentration by X ray spectrometer. As the bulk density of the soil increases, the concentration of quartz crystals per unit volume of the soil will increase and result in more intense diffraction lines. Though Watson and Jeffries reported the technique to be satisfactory, the literature does not indicate any further development or use of the method.

The gamma ray transmission method, which appears to have been first developed by Vomocil (1954) for measuring bulk density of soil, is most commonly used. The basis of the technique is the existence of a linear correlation between soil materials and the diminution in the energy intensity of certain gamma radiation photons when these are passed through a given thickness of soil. The diminution occurs by both complete absorption of some photons by pair production and photo-electronic effects, and by partial reduction in the energy of some other photons as they collide with the soil materials and scatter. The remainder of the photons are transmitted directly through the soil without any loss of energy. Therefore, they are fewer in number but maintain the same energy as at the source (Freitag, 1971). Consequently, two types of instruments have been developed to detect the dissipation, these are:

1. Back scattering. In which the intensity of reduced-energy photons is detected. As the bulk density of the soil increases, more collisions will take place, which result in more photons of reduced-energy; therefore, the counting rate, over a given interval of time, increases at the detector.
2. Transmission. In this type, the intensity of those photons which have maintained the original energy after transmission through the soil is detected; therefore, as the bulk density of the soil increases, less photons will be so transmitted and the count rate, over a given interval of time, decreases.

The instruments used in these techniques contain a radiation source and a detector, which are arranged in such a way as to delimit a known section of the soil. As the physical basis of the technique is the interaction between the gamma rays and the electrons of the soil materials, specifying this section of the soil, i.e. the distance between the source and the detector, is necessary to enable an accurate interpretation of the interaction of electron-to-mass ratio of the soil. This specified distance is that which is used when the instrument is calibrated (Freitag, 1971). Maintaining this distance in the "single tube probe" is achieved by fixing both the source and the detector in one tube, and separating them within the tube by a lead shield which allows the rays to pass through the surrounding soil only. Hence, a spherical body of the soil of 20-75 cm in diameter (Blake, 1965) is investigated. As this thickness is beyond the interests of many agronomists, who are interested in thinner layers, they prefer (Vomocil, 1957) the "double tube probe", which confines a horizon of a few centimetres vertical thickness between the two tubes. In the double tube probe, the two tubes, one containing the source and the other one the detector, are fixed in order to maintain the distance between them. The surface gauge (Freitag, 1971) is another device in which the source and the detector are placed on the soil surface with a fixed or adjustable distance between them. When such a device is used on a rough surface, levelling of the surface is necessary. Single tube probes and surface gauge devices are mostly used in the back scattering method, and double tube probes are commonly used in the transmission method (Blake, 1965).

Soane (1968) modified the standard transmission technique, i.e. tubular access of double probes, in such a way to permit both vertical and horizontal scanning. The equipment, which makes the planar access of the probes possible, involves inserting two mild steel plates into the soil to the desired depths using an alignment frame to insure a specific horizontal distance between them and keeping them parallel. The horizontal movement of the probes is achieved by a control frame placed on the alignment frame which can be advanced by hand in the increments desired. In this technique the mild steel plates must be included in the calibration. Soane reported that the technique is satisfactory for measurements of the abrupt changes in bulk density of the soil which may occur in field tillage studies.

The most widely used sources of gamma radiation are Cobalt 60 and Caesium 137. The size of the source required for a satisfactory counting rate depends on both its distance from, and the efficiency of, the detector (Vomocil, 1957). These two are also important factors in determining the accuracy of the technique. Both Geiger-Muller tube and scintillation detectors are satisfactorily used in the technique. When small volumes of soil are investigated the scintillation detectors are reported to be more efficient (Vomocil, 1957; Pirie et al, 1968 and Freitag, 1971). The use of scintillation detectors is also recommended (Van Bavel et al, 1957) in the transmission method where back scattering, due to unavoidable geometry of the soil, results in secondary radiation which overshadows the primary radiation. When this is the case, and the detector is not sensitive enough to detect only the primary radiations, the results obtained from the counting rate tend to be higher than those predicted from mathematical equations. The ratio between these two values, known as the "build up factor", may have values from 1 to 50 (Van Bavel et al, 1957).

For obtaining numerical values of bulk density of the soil in the field, the technique requires correction for the moisture content of the soil, but as the interaction with the gaseous component of the soil is insignificant (Blake, 1965) its effect is negligible. The technique also requires conversion of the counting rate by repeated calibration with soils of known densities. Yet, the method is known to be a time saving one, for the procedure is simple and for statistically reliable comparisons a fewer number of measurements is required as, in contrast to other methods, the data can be obtained from the same points. It is also a nondestructive means of bulk density measurements at localized points of the profile, and involves a lower degree of error. However, its claimed disadvantages include radiation hazard, being expensive, the possibility of compacting the soil when the tubes are inserted and its limited practicability in soils of stony nature where both inserting the tubes and interpreting the obtained data are considerably difficult (Vomocil, 1957; Blake, 1965; Soane, 1970,a and Freitag, 1971).

Pore Size Distribution.

Proportions of various class sizes of soil pores are most widely calculated from the soil moisture characteristic curve using the following equation which is solved from the capillary formula:

$$d = 0.3 / h$$

where d is the diameter (in cms.) of the pores which retain water against h cm. water tension. The method, which was proposed by Leamer and Lutz (1940), and Childs (1940), is based on the relationship between the height of water rise (h) in a capillary tube and the diameter of the tube (d) on the assumption that when a presaturated sample of the soil is subjected to a tension of h cm. water, the volume of water retained by the sample, when equilibrium is reached, is equal to the total volume of pores having an effective diameter not greater than d (Vomocil, 1965).

The key to the procedure is to place, with a good contact, a saturated sample of the soil on a membrane which allows the release of the excess water, at a reasonable rate, when the desired tension is established in the soil, then to determine the moisture content of the soil gravimetrically after equilibrium is reached. The establishment of the tension is achieved by creating a differential pressure between the two sides of the membrane either as a positive pressure in a chamber on the sample side of the membrane or as a negative pressure (suction), i.e. a continuous water column, on its other side. The pressure membrane and pressure plate (Richards, 1947) are examples of the former method which are usually used for tensions up to 15 bars, and the tension table (Clement, 1966) and sand tanks (van der Harst and Stakman, 1965) are examples of the latter method which are used for low tensions, i.e. 1/10 bar.

To meet its function satisfactorily, the membrane should have the following properties:

1. To maintain the required suction. This necessitates its air bubbling value, which depends on its maximum pore diameter, to be greater than the maximum suction used.
2. To have maximum permeability for the applied suction, i.e. homogeneous porosity.
3. To permit a good contact to be established between its surface and the soil sample.
4. To resist damage resulting from the pressure.

The most commonly used membrane materials for tensions up to 1/3 bar include sintered glass, filter paper, asbestos and sand and clay columns of proper thickness and particle size range, and for higher tensions ceramic plates, cellophane and sausage casings.

The only criticisms which the methods has received include the errors which may result from the relatively high impedance of the membranes either due to intrinsic properties of the material, especially those used for high tensions, or to eventual clogging of their pores by fine particles. Other errors may result from the wetting methods and associated ageing effects, such as the time necessary for saturation and the initial production of a stable structure which would resist further changes during equilibrium (Hillel and Mottes, 1966).

The interaction between the solid and water fractions of the soil, which may involve changes produced by shrinkage and swelling of clay particles and incipient failure of the aggregates is claimed by Quirk and Panabboke (1962) to result in some alterations in the geometry of the pores. To avoid such interactions, they recommended the use of non-polar liquids, such as benzene or tetrachloroethane, as the wetting agents. Furthermore, they were of the opinion that tetrachloroethane, which is of low vapour pressure, should be used when the procedure requires exposing the samples to evaporation. Currie (1966) was of the same opinion and used kerosene for his "crumb porosity determination" technique.

Klock et al (1969) used the "mercury intrusion" method for pore size distribution determination. Their technique is also based on the capillary phenomenon, and involves the use of a "porosimeter" by which mercury, from a reservoir in direct contact with the soil sample, is pressed into the soil pores by applying known pressures. The change in the volume of mercury in the reservoir is then accurately measured and related to the radii of soil pores which are filled by the applied pressure according to the following formula:

$$P = 2\,\sigma \cos \phi \,/\, r$$

in which P is the applied pressure, σ is the surface tension of mercury, ϕ is the contact angle and r is the pore radius. Though they reported satisfactory results of the method, Currie (1966) had previously stated that, in such techniques, the high pressure used for injecting the mercury into the soil pores may result in the breakdown of aggregates when dry and their deformation when wet.

Day and Holgren (1952) studied the change in the pore system of the soil at different stages of compaction microscopically from thin sections which were prepared in "Bodman-Rubin's" (1948) compaction apparatus. Though their method is a direct assessment of soil compaction, Cady (1965) stated that when a thin section technique is used for pore size studies, extra care and skill are required as colourless sand particles, if not properly dyed, cannot be distinguished from soil pores and that the lower end of the pore size which could be observed is limited by the thickness of the section. Cady was of the opinion that even in a well prepared section of 20-30 μm thickness, pores smaller than this in diameter may be overlapped or buried in the matrix. According to Quirk and Panabboke (1962) the technique requires examining a considerable number of sections to obtain a satisfactory picture of even the coarse pores.

Soil Fabric

According to Freitag (1971) the changes in soil fabric are among the most significant effects of compaction, but the determination of fabric and fabric changes are extremely difficult. The physical constitution of a soil material, as expressed by the spatial arrangement of the solid particles and associated voids, is the basis for the fabric characteristics of the soil. Therefore, it should be described in terms of orientation and distribution patterns of the primary particles, compound particles and voids (Brewer and Sleeman, 1960). Accordingly, Brewer and Sleeman (1960, 1962) produced a systematic descriptive method for soil structure and fabric studies which is mainly based on megascopic and microscopic examination of soil constituents. In their system the suggested methods of examining and expressing the voids and the orientation patterns could be of high value for comparative studies in soil compaction investigations. As for the voids, they suggest that they should be divided into inter-pedal and intra-pedal voids, then, the intra-pedal voids, which provide a means for describing the micro-structure of the soil, to be subdivided to:

1. Macrovoids: whose shortest dimension is greater than 75 μm.
2. Mesovoids: whose shortest dimension is between 30 - 75 μm.
3. Microvoids: whose shortest dimension is between 5 - 30 μm.
4. Ultramicrovoids: whose shortest dimension is less than 5 μm.

For the orientation patterns, they suggested that the way in which any constituent individuals, such as skeleton grains, peds, pedological features or voids, are arranged with regard to each other, can be used as the basis for defining four types of orientation, these are:

1. Strongly oriented: in which more than 60% of the individuals have their principal axes within 30° of each other.
2. Moderately oriented: in which 40 - 60% of the individuals have their principal axes within 30° of each other.
3. Weakly oriented: in which 20 - 40% of the individuals have their principal axes within 30° of each other.
4. Unoriented: in which there is no preferred orientation.

However, the literature does not indicate any use of these methods of soil fabric description as a means of soil compaction measurements. Nevertheless, Fitzpatrick (1971) included soil fabric in the list of the aspects of soils which are usually studied in thin sections. He, furthermore, stated that thin section morphology can be regarded as an extension of structure being concerned with the identification and the study of the organization of the soil constituents including the pores and pore space. Freitag (1971) was of the opinion that visual observations of soil fabric, especially by experienced observers, are useful and reliable means of estimating the amount of compaction the soil has received.

Soil Strength

The relationships between soil strength and its bulk density at given moisture contents (Fig. 15) are the basis for determining the degree of compactness of the soil from its strength data.

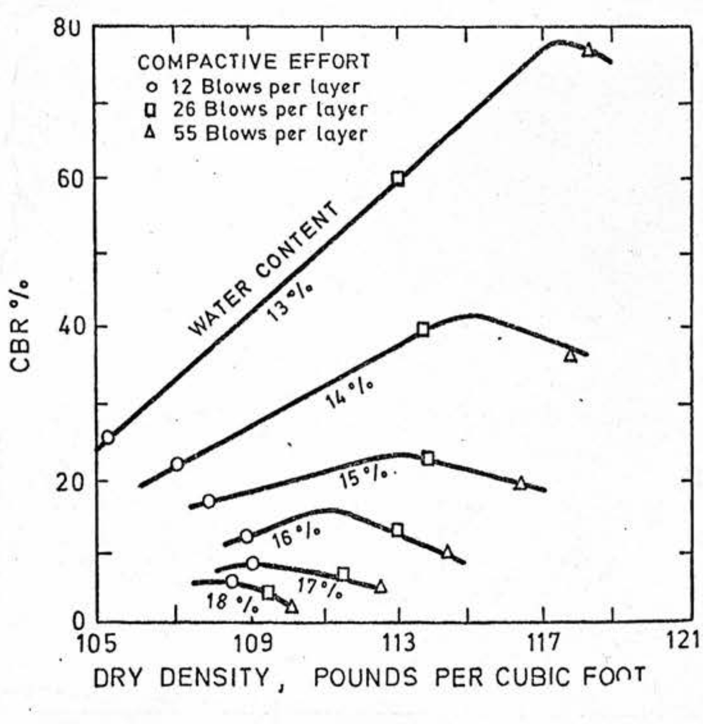


Fig. 15. Bulk density-strength (in CBR) relationships of a fine-grained soil at different moisture contents. (After Foster, 1955, quoted by Freitag, 1971).

The instruments used for soil strength measurements are either those which measure the shear resistance of the soil or those which measure its penetrability. The penetration tests are the common ones in the agricultural field as their interpretation in terms of soil compaction and bulk density is more suitable than those of shear tests (Freitag, 1971). However, the interpretation of penetration tests in terms of a single soil property is far from easy, as the obtained data represent a combination of all the properties of the soil which determine its cohesive and frictional characteristics. According to Baver et al (1972) the penetration resistance of a soil is an integrated index of soil compaction, moisture content, texture and type of clay mineral. Soane (1970,a) added the type of the penetrometer and its mode of use to the factors which cause the variability of the results and hence the difficulty in an accurate interpretation of the data. Nevertheless, the method is quick and cheap (Soane, 1970,a) and is a reliable means for studying the change in the level of tilth and compactness of the same soil (Vomocil, 1957), or for rapid comparison of soils of which the properties lie within a narrow range of variability (Bodman, 1949).

The types of penetrometers vary in size, shape and the manner of their insertion of the soil. The most common shapes are flat plate tips, both circular and rectangular, and cone shaped tips. The latter are the widely used ones in the agricultural field as they provide data on the penetrability of the entire profile, while the former, which are more common in engineering works, evaluate the rate at which the penetration resistance under the tip, which is of a few square inches in surface area, increases with depth of penetration

(Freitag, 1971).

The types of penetrometers, in regard to the manner of their insertion of the soil, fall into two categories: the impact type, such as hammer blows or falling weight, which is more common with hard soils, and the continuous stress recording type, which when inserted into the soil provides data indicating the force required for penetrating localized points of the profile.

The standardized units of measurement are: CBR, the California Bearing Ratio, which expresses the ratio of penetration resistance with a standard material under the same test conditions, and CI, Cone Index, which expresses the resistance in units of lb/in^2 when used with a cone of 0.5 in^2 cross section.

AGRONOMIC EFFECTS OF SOIL COMPACTION

Through the alterations, caused by compaction, in the strength, total porosity and pore-size distribution of the soil, the soil factors which are related to the growth of plants are affected. The response of the growing plant to such effects is either direct, such as the ease of root penetration in the soil, which is closely related to soil strength, or indirect through soil water, soil air, soil temperature and the accessibility of nutrients in the soil, which are all related, to various degrees, to total porosity and/or pore-size distribution. Barley and Greacen (1967) pointed out the extreme dependence of these factors on each other. Furthermore, the interactions between these factors and the metabolic processes, which influence the amount of growth, is of great significance (Raney and Adminster, 1961). Therefore, the relationships between the two complex systems of soil compaction and the growing plant are of great complexity (Rosenberg, 1964) and of considerable importance in determining the yield (Vomocil and Flocker, 1961).

The complexity of the metabolic processes, however, is not directly concerned in this discussion. Nevertheless, it clearly involves, in addition to various soil factors, both plant factors, such as the type of crop and its stage of growth, and weather factors such as the solar energy, temperature, humidity, wind and rainfall (Salter and Goode, 1967).

The specific effects of compaction on each of the above mentioned soil factors (Mechanical impedance, soil water, soil air, soil temperature and nutrient movement in the soil), although they will be dealt with separately in this discussion, are, in terms of their influences on plant growth, practically and for experimental purposes, almost inseparable

(Gill, 1961; Raney and Adminster, 1961; Barley and Greacen, 1967 and Taylor, 1971). Just as an example, Raney and Adminster demonstrated that the role of soil water extends to controlling soil strength, air, temperature and nutrient movement. Barley and Greacen (1967) stated that the response of the plant to a change in one factor may modify its response to another. Rosenberg (1964) stated that, because of the variation in the metabolic processes at different stages of growth, the soil factors which become critical vary with time. Hence, whether a given increase in the compactness of the soil will hamper or improve plant growth depends on whether the soil is more loose, at, or more compact than the optimal density for the season and stage of growth of the crop. The "wheel track corn planting" method, in which the corn seeds are sown in the wheel tracks (Peterson, 1960), is an example of taking advantage of benefits of early compaction on a specific crop or soil. In this method the moderately compacted soil under the wheels provides a seedbed which favours germination and the loose soil between the rows is an excellent rootbed. Archer and Smith (1972) concluded that management of the soil and assessment of bulk density during the life of the crop must take account of several considerations. Furthermore, the soil environment which is generally accepted to favour plant growth during a season consists of a period in which soil density is reduced by tillage treatments followed by a gradual re-establishment, naturally, of a degree of compaction which approaches that of the soil before ploughing.

In summary, the literature indicates that, if over-compaction is kept at a minimum, the role of compaction in influencing the complex interactions of the factors of soil-plant relationships cannot necessarily be considered as being detrimental.

Mechanical Impedance

The literature on the effects of soil compaction on the strength of the soil has been reviewed and discussed in detail by Bekker (1961) and Chancellor (1971). The consequent effects of soil strength upon root penetration and hence on plant growth have been discussed by Lutz (1952), Gill (1961), Barley and Greacen (1967) and Taylor (1971), and a summary of the literature is given by Commonwealth Agricultural Bureaux (1972,a).

The literature reveals evidence of the important role of the moisture content in determining compaction-soil strength relationships. In brief, at a given degree of compaction, the strength of the soil decreases with increase in the moisture content, and at a given moisture content, strength of the soil increases with increase in the degree of compaction. From a mechanical point of view this concept serves very well, but from an agronomic point of view the situation is further complicated by addition, to the relationships, of complex biological processes. The experiments which have been conducted to study the effects, on plant growth, of soil compaction through the resultant alterations in soil strength alone have, therefore, resulted in only meagre information, simply because of the difficulties in isolating these effects from the others of the complex interaction. Nevertheless, in some of these experiments the interaction is minimized or evaluated, and from their results the considerable role of mechanical impedance in influencing root growth and seedling emergence is concluded (Taylor, 1971). Vanden Berg (1961) was of the opinion that a special field of study of plant mechanics is needed which would relate plant growth to deformations and strengths of soil. In fact, an approach in this direction has been attempted more than 80 years ago. Gill and Bolt

(1955) translated the work of Pfeffer (1893) in which the relationship was studied by using a special apparatus which allowed seedling root pressure measurements, and a penetrometer which had a tip similar, in size and shape, to that of the root for measuring the external work which the root would have to do to penetrate the soil.

When a root penetrates the soil, the root pressure has to overcome the point resistance and probably root-soil friction. It is the turgor pressure within the elongation region of the root which results in the root pressure (Taylor, 1971). This is evident from the results of an experiment by Gardner and Danielson (1964) which show that cotton root penetration decreased with increasing salt concentration in the soil solution. Barley and Greacen (1967) added that as cell wall strength, combined with the turgor pressure, prevents bending of the roots, it should be included in assessing the penetrating ability of the root. The energy requirements to produce the root pressure to cope with the problem of mechanical impedance may, according to Gill (1961), shift the energy balance within the plant so that more energy is used by the roots.

Various techniques have been developed for measuring the root pressure of different plants (Gill and Miller, 1956; Gardner and Danielson, 1964; Stolzy and Barley, 1968; Eavis et al, 1969 and Taylor and Ratliff, 1969) and several types of penetrometers have been used by the workers in the field of root growth-soil strength relationships (Commonwealth Agricultural Bureaux, 1972,b).

Although penetrometers provide data which indicate the strength of the soil, and the root pressure data indicate the penetrating ability of the roots, these two values are useful in correlative studies only for discrepancies arising (Barley and Greacen, 1967) because:

(1) roots are flexible and tend to grow around obstructions; moreover, the shape of the root is influenced by the resistance of the soil. (2) as a result of anisotropic properties of roots, the stress distribution around the root is different from that around the penetrometer; furthermore, friction and adhesion between the soil and the root may differ from those between the soil and the penetrometer. (3) uptake of water by the roots causes local changes in the pore pressure and moisture content, consequently the strength of the soil is influenced. (4) in saturated soils, the roots create additional opportunities for drainage.

From the results of laboratory experiments, Stolzy and Barley (1968) reported an example in which the axial pressure exerted by a pea root tip was only 6.1 kg cm^{-2}, while according to the penetrometer reading, it should have exerted 7.3 kg cm^{-2} to penetrate the soil. Therefore, experimenters usually prefer relating the penetrometer resistance to root growth parameters other than root pressure, such as percentage of roots penetrating a fixed area (Taylor and Ratliff, 1969), rate of root elongation (Taylor et al, 1967), weight of root systems (Zimmerman and Kardos, 1961) and root-to-shoot ratio (Wiersum, 1957). Taylor et al (1966) found a curvilinear inverse relationship between penetrometer resistance of a 2.5 cm layer of four soils compacted to various degrees and the percentage of cotton taproots that penetrated these layers. Taylor and Gardner (1963) reported that both percentage of roots penetrated the soil and the rate at which they grew were reduced by an increase in soil strength. The literature contains a considerable number of reports of experiments conducted on various plant species which show a similar general pattern of decrease in the rate of growth with the increase in soil strength (Commonwealth

Agricultural Bureaux, 1972,a).

Under the heading of "Mechanic impedance", a review of literature is presented by Rosenberg (1964) in which the experimenters have merely demonstrated empirical relations between bulk density and growth. In these experiments the upper limits of bulk densities of various soil types at which different plant species can grow are pinpointed within a reasonably narrow range. However, as a soil strength parameter, bulk density does not include the deformability of the soil, i.e. it represents the pore space available for root development as constant. Barley and Greacen (1967) stated that the rigidity or deformability of the matrix should be considered in any parameter when used for evaluating the mechanical resistance of the soil. Wiersum (1957) studied the effect of pore size on root growth by allowing the root tips of various plant species to grow through both sintered glass discs with pores of 500-200 μm, 205-150 μm and 150-90 μm, and sands of the particle size range of 1200-210 μm, packed in glass tubes of different diameters (5-20 mm). From his experiments, in which the media were not deformable by the growing roots, Wiersum demonstrated that roots penetrate only those pores of diameter in excess of that of the root tip. Taylor and Gardner (1963) found that the correlation between root penetration and penetrometer readings was much closer than that with bulk density. However, under saturated conditions, Kar and Varade (1972) found that rice growth was more significantly related to bulk density than to soil strength. Wilkinson and Duff (1972) reported that root weights of three grasses, grown in a growth chamber increased with bulk density in the range 1.1 to 1.4 g cm^{-1}.

The factors which play a major role in governing the ability of plant roots to penetrate impeded soils are aeration, which affects respiration response, and moisture, which affects cell turgor and root rigidity (Barley and Greacen, 1967). For evaluating the interaction between soil strength and aeration, Gill and Miller (1956) devised a "growth chamber" which permitted measuring the root growth rate of corn seedlings under varying degrees of mechanical impedance and oxygen supply. They found that the rate of growth of unimpeded roots declined when oxygen supply was below 10% of atmospheric air, but the growth of impeded roots, under similar conditions, was seriously reduced. These results led Gill and Miller to conclude that decreased oxygen supply in the root zone decreases the maximum pressure which the root can develop. Gardner and Danielson (1964) reported that decreased aeration, as measured by CO_2 content of the soil lowered the penetrating ability of cotton roots to impeding soils. However, from a laboratory experiment, Phillips and Kirkham (1962,a) concluded that the degree of compaction, of a Colo clay, and not the free pore space, which was regulated by maintaining the soils under 10 and 100 cm water suction, reduced corn seedling root growth.

At equal soil strengths, the effect of soil water suction on root penetration is reported (Taylor, 1971) to be small until the suction value exceeds 0.7 bar. Barley et al (1965) claimed no difference in the restriction of wheat and pea root penetration into the soil at a given degree of compaction at 0.3 bar and 0.7 bar, beyond that which they ascribed to the increase in soil strength. In a laboratory experiment Taylor and Gardner (1963) studied the effects of soil strength and moisture content on cotton root penetration into a fine sandy loam compacted to various levels under controlled aeration conditions. They reported a highly significant linear correlation between soil strength and root penetration, but the correlation between moisture content of the soil and root penetration was much less significant. Furthermore, they stated that there is a strength limit above which no root penetrates the soil, and that this limit is valid whether the high strength is caused by compaction or by decreased moisture content.

Soil Water

Soil compaction relationships to plant growth, inasmuch as soil water is involved, include, in addition to its influences on aeration, nutrient status and strength of the soil, important direct soil-water-plant relationships. Soil water-compaction relationships are, therefore, concerned in soil management, and could be of great importance, especially in arid regions, in solving water-use efficiency problems. Water-use efficiency, (E_a), in the following equation, is defined (Hillel and Rawitz, 1972) as that percentage of the water supplied by the source (W_a) which is added to the root zone in an available form (W_r) for use by evapo-transpiration,

$$E_a = \frac{W_r}{W_a} \times 100$$

By altering the pore system of the soil, compaction plays a big role in soil-water relationships through affecting the infiltration of water into, percolation within and retention by, the soil (Warkentin, 1971).

Reduction in the infiltration capacity of various soils as a result of compaction has been reported by a number of workers (Fischbach and Duley, 1950; Doneen and Henderson, 1953; Flocker et al, 1958; Vomocil et al, 1958 and Linartz et al, 1966). The results of an experiment by Steinbrenner (1955), as presented by Lull (1959), on the effect of compaction on infiltration rate, bulk density and macro-pores of the soil show that the infiltration rate is the most sensitive characteristic of the soil to compaction. Rowles (1957) stated that permeability and infiltration capacity of the soil depend, almost entirely, upon the nature of pore space. The change in pore-size distribution towards a smaller proportion of the large pores is considered by Vomocil and Flocker (1961) as a great consequence of soil compaction. Adams et al (1958) found a highly significant correlation between infiltration rate and large pore spaces of the soil which are drained at low tensions. Horton and Hawkins (1965), added that percolation is accomplished throughout most of the flow path by downward displacement of water previously retained by the soil at field capacity. Linartz et al (1966) reported that compaction due to 10 years grazing in a watershed significantly reduced the amount of large pores of the soil which are drained at 60 cm suction, and consequently the infiltration capacity was highly reduced. In field studies in Glentress Forest (Peebles-shire), Shali (1967) compared the infiltration capacity, and the related physical properties, of soils of forested and grazed areas which were comparable in all respects other than the system of land use. In one of the sites studied, the minimum infiltration capacity of the grazing area was 43.3 cc min^{-1}, compared with 70.1 cc min^{-1} in the area under the forest. This statistically significant difference was related partly to compaction of the soil by grazing. The total porosity of the mineral A horizon was 60.9% in the grazing area and 69.4% in the forested area. The corresponding values of moisture retained by these soils against 0.1 atm. were 46.6% and 44.9% leaving air filled porosities of 16.6% and 24.5% respectively at this suction. However, the level of significance of the correlation between the infiltration capacity and total porosity was only slightly higher than that with the air-filled porosity at 0.1 atm. suction, which indicates that the micropores are also contributing to the downward movement of water, probably by displacement as was concluded by Horton and Hawkins (1965).

Infiltration refers to the process whereby water enters the environment of the soil through its immediate surface. It is, in fact, dependent on the rate of the transmission of water through the soil profile which is usually referred to as percolation (Baver et al, 1972). Warkentin (1972) demonstrated that the volume of water flowing through a tube per unit of time, according to Poiseulle équation, is proportional to the fourth power of the radius of the tube, i.e. halving the diameter of the tube decreases the volume of flow by a factor of 16. Therefore compaction, by reducing the volume of large pores, has a great effect in reducing water transmission under saturated conditions. However, the situation in the pore system of the soil, particularly in the field, is not so simple, as the soil is not always saturated, and the soil water, because of a number of very strong attractive forces between surfaces of soil particles and water molecules, has a potential energy lower than that of free water (Gardner, 1968). These forces are: (1) those of solid-water interfaces which originate from the attraction between the ions of the water molecules and of the electrical double layer at the charged surfaces of clay particles, and result in the adsorption, around clay particles, of thin water films which are not free to move (Warkentin, 1971), and (2) those of the water-air interfaces which result in the capillary potential ψc and originate from the tension pressure, which derived from the curved menisci at the water-air interfaces and related to the radius of the curvature

(Childs, 1940 and Gardner, 1968) by the following equation:

$$\psi c = -2\ \sigma/r$$

where σ is the surface tension. The matric potential of soil water, which is due to these forces, plays a big role in determining the retaining ability of soil for water and its movement especially in layered soils (Gardner, 1968; Warkentin, 1971; Baver et al, 1972, and Taylor and Ashcroft, 1972). In fact the capillary potential, which depends on the pore system of the soil and hence on the degree of compaction, is the major component of the matric potential ψm, and both terms are usually used synonymously in the literature (Day et al, 1967; Slayter, 1967 and Kirkham and Powers, 1972). The relation of matric potential to (r) in the above equation is the basis for the most commonly used method for the determination of pore-size distribution of the soil and its alteration by compaction. On the other hand, specific matric potential values have been used as the upper and lower limits of the retaining ability of soil for available water for plants (Hendrickson and Veihmeyer, 1945), and the variation in its values within the soil is used as the key for studying unsaturated flow of water in the soil for it contributes in governing the flow as a component of the total potential gradient (Miller and Klute, 1967; Gardner, 1968, and Taylor and Ashcroft, 1972).

Water movement in the soil

The modes of water movement in the soil are:

1. the viscous flow through liquid-water filled pores, and
2. the diffusion of vapour through air-filled pores.

Although both of these modes contribute to the total movement, the viscous flow is the dominant mode unless the soil is quite dry and temperature gradient is high, in which case vapour flow becomes the major mode. Only viscous flow will be discussed herein, but the general principles of movement are almost the same (Miller and Klute, 1967).

The rate of viscous flow of water in the soil depends on both the driving force and the permeability of the soil to liquid water, according to the general flow equation (Klute, 1965) which is based on Darcy's law:

$$v = -K\nabla H$$

where v is the volume of water passing through unit cross sectional area of the soil per unit time, K is the permeability of the soil to water, i.e. hydraulic conductivity and ∇H is the driving force, i.e. the hydraulic potential gradient. The magnitude of both factors involves a number of soil factors such as pore-size distribution, volumetric moisture content and matric potential. Gravitational, pressure, solute and temperature potentials, which are considered as external forces (Taylor and Ashcroft, 1972) are also involved.

The driving force

The driving force, which may result in viscous flow of water through the soil from regions of higher total potential to adjacent regions of lower total potential, is the total hydraulic potential gradient, dh/ds, where s is the distance in the direction of flow. Assuming isothermal conditions and assuming negligible solute potential, as the soil is not semipermeable, the potential gradient between any two points in the soil will depend on the hydraulic potentials of the points. The components of the hydraulic potential, ψh, then are, (Gardner, 1968 and Taylor and Ashcroft, 1972):

$$\psi h = \psi m + \psi p + \psi g$$

where ψm, ψp and ψg are the matric, pressure and gravitational potentials respectively. ψm in saturated soils and ψp in unsaturated soils are negligible (Gardner, 1968).

The matric potential is affected by compacting the soil as a result of the alterations in pore-size distribution and the consequent changes in the capillary potential (Taylor and Ashcroft, 1972). Taylor and Box (1961) studied such effects by applying mechanical pressure to change the bulk density of soil aggregates in a special device which allowed:

1. maintaining the moisture content constant at three levels during compaction and afterwards,
2. controlling the increment in bulk density (from 1.1 to 1.4 g cm^{-3}) through the mechanical pressure,
3. keeping the atmospheric pressure inside the system constant and equal to that of the laboratory, and
4. recording the matric potentials of the soils when the compacting pressure was still applied after achieving the desired bulk density as well as when it was released.

From their experiment they drew two important conclusions:

1. The increase in bulk density, in the range 1.10 to 1.35 g cm^{-3}, resulted in an increase in the matric potential from -27 to -23, from -46 to -41 and from -58 to -52 joules kg^{-1} (1 joule kg^{-1} = 10 millibars) at the three moisture contents investigated (23.0%, 19.7% and 17.5%) respectively. They reported that although these increases are relatively small, they are significant in respect to the water potential.

2. The matric potentials at various bulk densities of the soil were very close when the mechanical pressure was released to those when the mechanical pressure was still acting. This conclusion let them to state that the overburden pressure does not affect the matric potential beyond that which is attributable to the changes in bulk density, therefore, overburden pressure should be included in the matric potential and not to be considered as one of the components of the total potential.

Box and Taylor (1962) were of the opinion that the commonly observed phenomenon of hysteresis may be explained in part by changes in bulk density resulting from wetting and drying.

Although an increase in the matric potential, in homogeneously compacted soil affects the soil-water potential, i.e. retainability of water by soil, it does not affect the gradient potential, i.e. the driving force, within the soil. In such soils the matric potential is a function of water content only (Swartzendruber, 1966). However, in agricultural soils the situation usually consists of layers of different degrees of compactness. The flow of water in such layered soils has been analysed both numerically and experimentally by, among others, Takagi (1960), Eagleman and Jamison (1962), Hanks and Bowers, (1962) and Miller and Gardner (1962). Swartzendruber (1966) postulated that the hydraulic conductivity of the least permeable layer is not the sole determining factor for saturated flow of water in layered systems. According to Warkentin (1971) as a result of the differences in the pore systems of the two layers, the pressure gradient is no longer uniform, and the large pressure drop which occurs through the least permeable layer results in a higher driving force and consequently a flow which is higher than that resulting from a uniform gradient. The unsaturated flow through layered systems, however, is different and the matric potential gradient plays its role in it as explained by Warkentin (1971) as follows: When a layer of high bulk density overlies a layer of lower bulk density the wetting front of downward movement of water does not move immediately across the boundary between the two layers, because the soil suction in the top layer, with a higher proportion of small pores, is too high to permit water to be drawn to the large pores of the lower layer, but if the water supply to the upper layer continues, the situation will gradually alter as with the increase in the moisture content of the upper layer its suction decreases till it becomes low enough to allow water to move into the large pores of the lower layer.

Soil permeability

The term refers to the ease with which gases and liquids can pass through the bulk of the soil. It is a property of the soil and is frequently replaced by the term "intrinsic permeability". As the passage of these materials varies not only with the properties of the soil, but also with the properties of the materials, the term "hydraulic conductivity" is more commonly used in soil-water movement discussions, as it also takes into account the viscosity of water. The hydraulic conductivity "k" numerically is equal to the permeability "K" divided by the viscosity of water η,

$$k = K / \eta$$

In this discussion both the composition and the temperature of the soil solution, which determine the viscosity of water, are assumed constant and the terms, permeability, intrinsic permeability, and hydraulic conductivity, are synonymously used.

Milford et al (1961) studied the effects of compaction on a number of physical, chemical and minerological properties of the soil and concluded that K is the only parameter capable of consistent detection of soil compaction. Childs (1957) stated that K is a property of the pore space of the soil, and that the configuration of the pore space influences the permeability of the soil. Such configurations, inasmuch as soil compaction is the cause, are related to a decrease in the total porosity and alterations in the pore-size distribution.

Under saturated conditions, where all the pores are full of water and are available for conducting liquid water, the hydraulic conductivity is at maximum. The reduction in the total porosity by compaction, therefore, results in a reduction in the maximum saturated flow. Warkentin (1971) summarized the results of a number of investigations to show such effects of compaction and demonstrated that the logarithm of the saturated hydraulic conductivity is linearly related to the void ratio. Childs (1957) was of the opinion that it is not only the total porosity which affects the hydraulic conductivity, but also the continuity and the volume distribution of the pores. Childs demonstrated that a soil which has a majority of fine pores will have a lower conductivity than a soil which has a majority of coarse pores even when their total porosities are equal, because viscous flow is faster in large channels as most of the flow takes place away from the walls. Accordingly, compaction, by proportionally increasing the fine pores of the soil, results in a further lowering in hydraulic conductivity.

The dependence of the permeability of the soil on its pore system is the basis for a method, proposed by Reeve (1953), for measuring the stability of soil structure. In this method, the ratio of permeability of soil to air to that of the soil to water is taken as an index for assessing the stability of the pores. Laliberte and Brooks (1967), experimenting on three soils varying in texture from silt loam to sand and using a light hydrocarbon oil as the wetting fluid which eliminates the swelling effects, found that the saturated permeability increased several-fold as the porosity increased from 0.38 to 0.58. Sharma and Uehera (1968) found that the macro-structure effects on water movement in two latosolic soils were more pronounced at low tensions (0.0 - 0.2 bars) when the moisture content of the soil approximates to saturation, while at higher tensions, the micro-structure influenced the fluid flow of water.

With the reduction in the degree of saturation and the introduction of an air phase to the system, the total pathway available for the flow of liquid water is no longer equivalent to the total porosity. When a tension is applied to a saturated soil, the large pores which contribute to a major part of the total porosity are first drained of their water and a sharp decline in the conductivity occurs. Under unsaturated conditions, "unsaturated flow" takes place for which the terms "unsaturated hydraulic conductivity" or "capillary conductivity" are usually used, and a dimensionless factor λ is added to the general flow equation which then becomes:

$$v = -k\lambda\Delta H$$

The value of λ varies from 0 in dry soils to 1 in saturated soils (Baver et al, 1972). Baver et al (1972) stated that the matric potential becomes an important indirect factor in determining the permeability of the soil under unsaturated conditions, simply because it is related to the quantity of water-filled pores under various tensions. Therefore, the alterations in pore-size distribution by compaction towards a high proportion of small pores and the consequent changes in the matric potential result in an increase in the unsaturated hydraulic conductivity. The following illustration is presented by Taylor and Ashcroft (1972) on the relationships between the unsaturated hydraulic conductivity and the matric potential for several soils.

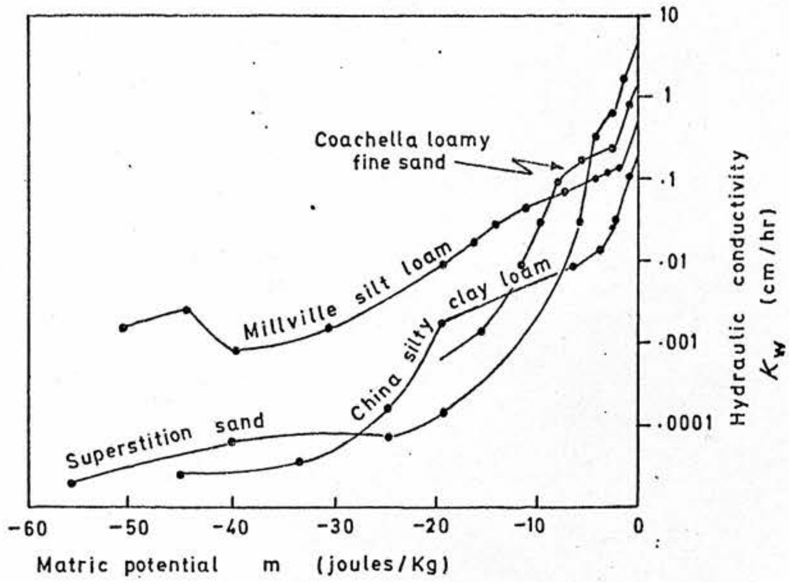


Fig. 16. Hydraulic conductivity as a function of the matric potential for several soils. (After Taylor and Ashcroft, 1972).

Kemper et al (1971) presented evidence that the conductivity of a clay loam, having a bulk density of 1.1 g cm^{-3}, at suctions greater than that of field capacity can be at least doubled by compacting the soil to a bulk density of 1.5 g cm^{-3}. Barden and Pavlakis (1971) concluded that the major factors which influence the permeability of unsaturated soils to water are structure and the degree of saturation, and that compaction can increase the permeability.

Although several methods are available for measuring the permeability of the soil directly both in situ and in the laboratory, the formulation of equations for computing the permeability from the pore system, though it has been attempted, seems to be difficult. Childs (1957) stated that permeability is one of the consequences of a specified physical make up which is not easy to assign in structured materials such as soil. The Kozeny equation, which relates the permeability to the porosity and the surface area of the particles is useful where the pores of the material are fairly uniform (Warkentin, 1971), but is difficult to apply to soils which are characterised by a wide range of pore sizes (Marshall, 1959). Therefore, the workers in this field have attempted to relate the permeability to specific pore volumes. In this respect, Baver (1938) proposed differentiating the capillary from non-capillary pores, and Nelson and Baver (1940) assigned those pores which are drained at 40 cm water suction as non-capillary pores. Smith et al (1944) suggested dividing the pores into three groups: those drained at suctions of 10 cm, between 10 and 40 cm and between 40 and 100 cm water, and giving weightings of 1, 1/4 and 1/10 to each group respectively. Childs (1957) claimed that the method of Childs and Collis George (1950) in which they used the whole range of the soil moisture characteristic allows for computing the permeability at any moisture content and that the computed values of permeability according to their method agree satisfactorily with measured values. Marshall (1958) derived the following equation for calculating the permeability from the size distribution of the pores:

$$K = e^2 n^{-2} \, [r_1^{\,2} + 3r_2^{\,2} + 5r_3^{\,2} + \ldots + (2n-1)\, r_n^{\,2}] \;/8$$

where K is permeability in units of cm^2, e is the porosity in $cm^3 cm^{-3}$ and n is the number of equal fractions of the total pore space represented in decreasing order of size by $r_1, r_2, \ldots, r_n$ cm. Marshall produced other forms of the equation for calculating the permeability from the moisture content of the soil under various suctions and also for calculating the unsaturated hydraulic conductivity.

The foregoing discussion reflects the important role of the pore size distribution in determining the permeability of the soil.

Soil Water Availability

Soil water availability to plants is a complex function of a number of factors which makes its definition difficult (Kramer et al, 1967; Slatyer, 1967 and Gardner, 1968). Generally speaking, in a given soil with a fixed root system or a root distribution which does not change rapidly, the effects of these factors can be related to:

1. The retaining ability of the soil for infiltrated water. This property of the soil is related to the Available Water Capacity (AWC) which is normally determined as the amount of water retained by the soil at field capacity minus the permanent wilting percentage.
2. The condition of the retained water in relation to plant response which according to Richards (1928) involves two notions: (i) the ability of plant roots to absorb the water with which they are in contact, (ii) the velocity with which the soil water moves to replace that which has been used.

Regarding the retaining ability of soil for available water, the concepts of field capacity (Veihmeyer and Hendrickson, 1927) as the upper limit and of permanent wilting percentage (Hendrickson and Veihmeyer, 1945) as the lower limit have served in classifying the soil water in descriptive terms, and allowed for measuring the AWC of the soil, in the early days. With the introduction of the parameter pF (Schofield, 1935) and the advent of the pressure membrane apparatus

(Richards, 1947) the basis for a continuous and quantitative measurement of the retentive properties of the soil to water was provided, and detailed examination of the soil matrix properties became possible. Consequently, the descriptive boundaries were substituted by, arbitrary but, precisely defined boundaries justified, to reasonable degrees, by empirical correlations with the practically important boundaries (Childs, 1972).

The permanent wilting percentage is universally accepted to be identical to the water content retained by the soil at 15 bar tension. However, Slatyer (1967) was of the opinion that, as the wilting of plants is associated with the osmotic characteristics of leaf tissues, it should not simply be related to the soil water potential alone. Nevertheless, for most crop plants the soil water potential at permanent wilting falls in the range 10 - 20 bar tension and the mean value of 15 bar tension is regarded as a soil constant useful for many practical purposes (Richards and Wadleigh, 1952). Richards (1954) considered the lower limit as an intrinsic property of the soil that is largely determined by soil texture.

The field capacity, on the other hand, depends in addition to the texture, on the variation throughout the profile of a number of factors such as pore-size distribution, structure, initial moisture content and hydraulic and drainage characteristics (Richards, 1954). Day et al (1967) stated that the concept of an upper limit of available soil water also involves plant and environmental factors which, being external to the soil, cannot be properly appraised by measurements made in the laboratory on samples removed from the profile. Therefore, the variation in the upper limit is, in general, found to be too wide to be regarded as a reliable soil constant (Slatyer, 1967). This, in fact, is well reflected by the discrepancies in the results of attempts which have been made to relate field capacity moisture contents to those retained by soil samples in the laboratory against specified tensions. Salter and Howarth (1961) considered 0.05 bar tension as useful for rough estimates of field capacity for sandy loams. Thomasson and Robson (1967) also used 0.05 bar tension as an approximate upper limit of the available water. From a survey of soils in South Central England, where matric suctions were measured frequently during 1962 and 1963, Webster and Beckett (1972) concluded that for freely drained sandy soils the 0.05 bar tension can be taken as the upper limit of the available water. For loams or clay loams, though the limit was generally 0.04 - 0.05 bar, they stated that it could well be as low as 0.02 bar. Their conclusions for clays, however, was that no single matric suction can be accurately detected in the sense of a definite and quickly attained condition, but the moisture content at the arbitrary tension of 0.05 bar is useful for practical purposes. Jamison (1953), on the other hand, used 0.33 bar tension for estimating the field capacity for four soils differing in texture. Although the 0.33 bar tension is reported, in literature reviews by Richards and Wadleigh (1952) and Marshall (1959), as being satisfactorily used on samples whose structure has been partly destroyed, the reviews show that, for naturally structured soils, the 0.1 bar tension is more commonly used. Salter et al (1967) found that approximation of field capacity to 0.1 bar tension is reasonable and Richards (1954) stated that, for sandy soils, it approximates satisfactorily the upper limit of available water under field conditions.

From the foregoing discussion it could be concluded that the lower limit of the AWC of the soil can be considered constant, and it is the upper limit which may be affected by management resulting in variations in the AWC. Structural changes and consequent alteration in pore-size distribution are important causes of such effects. Therefore, compaction, when it alters the pore-size distribution of the soil towards an increase in the total volume of small pores and a decrease in the total volume of large pores, theoretically should result in a higher moisture content retained by the soil at tensions approximating those of field capacity, and a lower moisture content at saturation. Jamison (1953), Hill and Summer (1967) and Archer and Smith (1972) found that compacting the soil to a definite bulk density increases the AWC. Warkentin (1971) summarized the results of a number of experiments to show that compaction increases water retention by the soil in the range where it is available for plants for both clay and sand. Another interesting approach in this direction has been made by Peters (1957) by separating the effects of the tension component from those of the moisture content component on the uptake of water by corn roots. Peters prepared four mixtures of silty clay loam and sand containing respectively 25, 50, 75 and 100% silty clay loam. These mixtures had the property of additivity of moisture content, with equal spacing, at tensions within the available range. The soil mixtures were brought to equilibrium with tensions of 0.33, 1, 1.73, 3 and 8 bars. Then 14 germinated corn seeds were allowed to grow in the mixtures which were placed in a special growth chamber for 24 and 48 hours, after which the rate of elongation was measured as an indicator of the water uptake. Root elongation increased linearly with the increase in the moisture content, tension being constant.

There seem to be two concepts regarding the ease of uptake by plants of the water held between the two limits. These are "equal availability" and "decreasing availability" as the moisture content approaches permanent wilting percentage. According to Gardner (1968) the concept of equal availability is supported by the fact that transpiration rate is found to be unrelated to soil water content over much of the available range, and the concept of decreasing availability is supported by various plant response measurements. However, in relating the effect of compaction to the true availability of the retained soil water to plants, no effect could be anticipated if the concept of equal availability is considered over and above the effect on the retaining ability of soil to water. When the concept of decreasing availability is considered, the effect of compaction appears to extend to the actual availability. Stanhill (1957) summarized and analysed the results of 80 experiments and found that in 66 experiments out of the 80, plant growth did respond, with significant differences, to differences in soil moisture regime. The results of the experiment of Peters (1957) also showed an increase in the uptake of water by the corn seedlings roots with a decrease in tension at the same moisture content. This led Peters to conclude that the uptake of water by plant roots is a function of both moisture tension and moisture content, and that the function of moisture content may be either through a capacity factor or a dynamic factor. Such findings, though they have been achieved through textural variation in the matrix properties of the soil, may safely be compared with those resulting from compaction in the sense that compaction may result in a situation where higher moisture content is held by the soil at the same tension. Evidence supporting such consequences of compaction has been presented previously in this discussion.

One of the causes suggested by Marshall (1959) for unequal availability of soil water to plants is the decrease in the permeability of the soil to water on drying and hence the reduction in the movement of water towards the root zone. Gardner and Ehlig (1962) concluded that impedance to water movement in the soil limits water availability, and Peters (1957) was of the opinion that water movement plays an important part in water uptake by plants. However, the effect of compaction on the unsaturated flow of water in the soil, which is the case in the field, has been dealt with previously in this discussion. Nevertheless, a complex of interactions between the factors of moisture content, moisture tension and permeability exists in the root zone which Marshall (1959) described as follows: "The reduced permeability on drying will be to some extent compensated by an increased suction gradient favouring movement towards the root hairs, but this compensation is accomplished at the cost of increased suction at the absorbing surface".

Soil Air

Grable (1966) defined soil aeration as "that part of the gaseous cycle involving the interchange of CO_2 and O_2 between the living organisms, soil and the aerial atmosphere". The removal of the toxic gases, including CO_2 and the supply of O_2 and other gases such as nitrogen and water vapour in dry soils, as well as the distribution of fungicides, nematicides, pesticides and fertilizers, when applied in the gaseous form, are of great agronomic concern (Currie, 1970).

The transport of gases in the soil, as any other transport phenomenon, depends on the conductivity and the gradient potential in the direction of flow (Currie, 1970). When the gradient is in the total pressure, due to factors which are external and usually temporary, such as diurnal and seasonal changes in the barometric pressure or in the temperature, the resulting flux is termed "mass flow". When the gradient is in the partial pressure, i.e. the concentration of the gas under study, due to various chemical and biological processes in the soil, which are continuous, the resulting flux is termed "diffusion". Diffusion rather than mass flow is considered to be the major process for the interchange of gases in the soil (Russell, 1952; Grable, 1966 and Baver et al, 1972). Percolating water may carry with it dissolved gases, and the gas movement may also take place in response to wind turbulence in shallow soils. According to Grable (1971) whatever the mechanism would be, compaction reduces soil porosity and limits gaseous movement. Compaction of the soil always reduces air permeability (Barden and Pavlakis, 1971) and air permeability being the transport constant for mass flow (Currie, 1970), the interchange of gases by mass flow is reduced. The transport constant for diffusion is the coefficient of diffusion of the gas in the soil. The coefficient of diffusion in porous materials D, in relation to that of the gas in air, i.e. in absence of obstruction, D_o, is found to be linearly related to the free pore space S over the range ($0<S<0.7$), which is encountered in the soil, by the following equation of Penman (1940):

$$D/D_o = 0.66\ S$$

However, Currie (1970) stated that in addition to the percentage of air-filled pores the tortuosity of effective path length must be considered when such equations are derived. Taylor (1949) demonstrated that with compaction, or increased moisture content, the rate of diffusion is decreased. Currie (1961) showed that adequate aeration is not only a function of active soil depth and the macro-diffusion coefficient, but is also a function of the micro-structure of any depth.

From a review of literature, Bateman (1963) concluded that corn growth may be retarded when the percent of air-filled pores at field capacity declines towards 10%, and experimentally showed that compaction of many soil types can reduce the air-filled pores to such a critical level. Vomocil and Flocker (1961) summarized the results of a number of field and greenhouse studies covering a variety of soils under varying conditions to show that, for a number of important crops, growth is appreciably reduced when the volume of air-filled pores is in the vicinity of 10 - 15% of the soil volume. Experiments by Grable and Siemer (1968) showed that only 3 to 4 percent of interconnecting air-filled pores in the soil were needed to maintain a level of O_2 high enough to support adequate respiration rates during the germination of corn seeds. Papendick and Runkles (1966) were of the opinion that as the rate of respiration is not constant, very high respiration can cause a period of deficient aeration in otherwise well aerated soils. Soane (1970,a) stated that though severe compaction can reduce the air-filled porosity of field soils to below 10%, proof is often lacking that oxygen deficiency was necessarily the cause of growth restriction since air-filled porosity values are correlated with bulk density and soil strength in compacted soils. According to Rosenberg (1964) compaction effects on plant growth need not necessarily involve impeded aeration particularly of medium and coarse textured soils. The results of an experiment by Archer and Smith

(1972), on four arable soils differing in texture, show that only in clay loam soils can increased bulk density in the field, as a result of compaction, reduce the air-filled porosity at 50 mbr suction to zero level.

Soil Temperature

Although the literature seems to contain no direct studies which clearly relate the effects, on plant growth, of soil compaction through influencing the thermal regime of the soil, evidence is available which shows the effect, in varying degrees, of soil temperature directly on the complex processes of growth such as germination, seedling emergence and root and vegetable growth of various plant species (Hagan, 1952), on accumulation of N and K in a number of crops (Richards, 1952) and on the uptake of P by oats and potatoes (Simpson, 1961). The indirect effects of soil temperature on plant growth include those on soil aeration and soil water relationships (Richards, 1952), decomposition and mineralization of organic matter (Russell, 1961) and microbial activities and associated alterations in the soil environment (McCalla, 1952). In greenhouse experiments Allmaras et al (1964) found a linear relationship between soil temperature, in the range of 60^{o} to $83^{o}F$ at 4 inch depth, and the ratio of dry matter of corn produced in mulched treatment to that produced in the unmulched treatment. They, furthermore, used their data for estimating the optimum soil temperature in the field.

The effect of soil compaction, on the other hand, on the thermal properties of the soil has been realized and investigated. Willis and Raney (1971) stated that compaction affects heat content and transmission in the soil by changing soil density, soil water relations and the magnitude of plant growth. Heat flux in the soil, as stated by Rosenberg (1964) is clearly related to its degree of compactness since the thermal conductivity of any porous material depends on the proportions of the matrix occupied by solid, liquid and gaseous phases and on the conductivity of each of these phases. From a review of literature, Richards (1952) reported that at constant moisture content, on average, for each 0.016 g cm^{-3} increase in density of the soil, its thermal conductivity increases by 2.8% for unfrozen and 3% for frozen soils. Data by van Duin (1963), as presented by Baver et al (1972), show that 50% decrease in the porosity of sand and of clay results in doubling the thermal conductivity. Nakshabandi and Kohnke (1965) found that thermal conductivity of dry soils increases with increase in bulk density and moisture content, and that mineral soils of different textures exhibit very different thermal conductivities at the same moisture content, but similar conductivities at moisture contents of the same tension. Their conclusions suggest that the effect of compaction on retaining ability of soil to water indirectly increases the thermal regime of the soil.

Stickler (1962) explained an increase in the yield of winter wheat and barley in Kansas, after the use of press wheels, as a result of compaction-thermal conductivity interactions giving rise to less freezing and less extreme temperature changes giving seedling winter hardiness. Van Duin (1954) concluded that, as far as soil temperature is concerned, fall ploughing is not desirable if winter crops, sensitive to cold, are grown, in the view of lowering temperature in winter and the increase in the daily amplitude. Gradwell (1963) was of the opinion that the gain in output produced by attainable increase in the soil density should be beneficial, if other circumstances are favourable, in reducing the severity of frost.

Soil Nutrient status

The nutritional status of the soil, in relation to plant growth and the yield, is governed by factors of intensity, capacity and rate of movement (Williams, 1962). If the indirect effects of soil compaction are disregarded, it can be assumed that the composition of the soil solution, i.e. the intensity factor, will not change as a result of compaction (Parish, 1971). In the field the capacity factor, however, depends on the volume of soil explored by roots, and hence, on soil physical properties and profile features (Williams, 1962). Therefore, when soil compaction, through increased soil strength, results in a restricted root ramification, the total uptake of nutrients, in general, will be reduced (Phillips and Kirkham, 1962,b). The other factor which is of great importance in bringing the soil nutrients' ions to proximity with the absorption site of the root, is the movement of nutrients towards the roots (Kemper et al, 1971). Both mechanisms of nutrient movement in the soil, namely, diffusion and mass flow, are affected by compaction. Cooke (1966) stated that changes that impair soil structure, not only interfere with root growth to nutrients, but also with the uptake by diffusion and mass flow processes. Graham-Bryce (1963) attributed the reduced rate of diffusion in the soil, as compared with that in aqueous solutions, to geometrical and electrical effects. Nevertheless, Graham-Bryce experimentally found that increasing bulk density, over the range; 1.34 to 1.64 g cm^{-3}, led to increased values of diffusion coefficient of Rb in heteroionic soils, and explained this effect of compaction as being due to the production of more continuous aqueous systems in the soil pores. Phillips and Brown (1965), however, found that the relationship between bulk density and the rate of diffusion is curvilinear, which they explained to be a result of obstructional effects of the solid phase at extreme degrees of compaction which eventually causes a decrease in the diffusion rate. Diffusion is the dominant mechanism for the transport of potassium and phosphorus, the compounds of which, especially of p, are characterized by relatively low solubility in water. Barber (1962) reported that, with adequate water movement in the soil, mass flow accounts for only about 1/100 of the total P and about 1/10 of the total K uptake. Cornforth (1968) stated that phosphorus moves to plant roots mainly by diffusion and a layer of 1-2.5 mm around the root is important. Nitrate nitrogen, on the other hand, is completely mobile throughout the soil profile and its movements follow very closely the movement of soil water (Bray, 1954). Kemper <u>et al</u> (1971) stated that the movement of nitrates, sulphates and other non-adsorbed anions depends to a large degree on mass flow of soil solution, and hence on the soil-water relationships.

Other effects of compaction on the nutrient status of the soil, which are indirect, include CO_2 accumulation which may affect the pH and consequently influence the availability of various nutrients. Compaction may also reduce oxygen supply and hence, influence the microbiological activities and the mineralization of organic compounds. Kemper <u>et al</u> (1971) presented data of Whisler <u>et al</u> (1965) which show that nitrogen mineralization from soil organic matter was reduced even by a slight increase in the level of compaction.

Phillips and Kirkham (1962,b) found that total uptakes of N, P and K per 20 corn leaves sampled at silking time were significantly reduced as a result of compaction but they stated that mechanical impedance as measured by bulk density was the physical property most highly correlated with the reduction of growth and the yield of corn. However, results of experiments by Flocker and Nielsen (1962) and Kubota and Williams (1965) showed that compaction had no apparent effect on nutrient uptake. Parish (1971) was of the opinion that the reduced yield due to compaction should be related to factors other than nutrient uptake, such as aeration, soil-water relationships and mechanical impedance. The effects of compaction on the nutrient status of the soil, according to Kemper et al (1971) can be either beneficial, through the resultant increase in the rate at which most nutrients move by both diffusion and mass flow mechanisms, or detrimental, as compaction results in a reduced mineralization of the soil organic matter.

SUMMARY

Compaction of the soil results in a closer packing of its particles, and hence in both a reduction in the total porosity and an alteration in the pore-size distribution. The compaction mechanism is a complex process in which a number of soil and force factors are interacting. The soil factors include texture, organic matter content, chemical and minerological composition of the soil and the soil moisture content at the time of compaction. The force factors include the type, amount and duration of the force and the way it is distributed on and within the soil.

The agonomic effects of compaction of agricultural soils include the changes in the factors of soil strength, soil water and air relationships, the thermal properties of the soil environment and the nutritional status of the soil. As these soil factors interact with each other and with the complex processes of the growth of both living root systems and soil micro-organisms, investigating the effect of compaction on any one of them alone is extremely difficult.

The review of literature reveals that soil water plays a double role in the agronomic significance of soil compaction. Firstly, at the time of compaction, the moisture content of the soil determines the resultant degree of compaction and, hence the consequent reduction in the total porosity and the alteration in the pore-size distribution. Secondly, in the compacted soil it is not only the soil-water relationships which are affected by compaction, but that soil water also plays a big role in determining the magnitude of the effects of compaction on the other soil-plant relationships, namely, the mechanical impedance, aeration, thermal properties and the nutritional status of the soil.

The objectives of this research work are to test the effects

on the available water capacity, of compacting the soil at a moisture content which is within the available range, and to relate such effects to the actual growth of established plants.

EXPERIMENTAL

METHODS AND MATERIALS

A. The Experimental Work.

The experimental work in this investigation included a pilot experiment carried out in May-July, 1971 and three major experiments carried out in July-November, 1971; May-August, 1972 and February-July, 1973.

The Pilot Experiment

This was a pot experiment carried out in the glasshouse to investigate the effect of moderately compacting the soil, at moisture contents near to that of its field capacity, on the percentage of micro-pores which hold available water. The effect was tested both by assessing the response of established plants to the theoretically expected increase in available water, and by comparing data obtained from the determination, in the laboratory, of the available water capacity in compacted and non-compacted soils. The suitability, as a test plant, of three species sensitive to moisture stress, namely, red clover (Trifolium pratense), black mustard (Brassica nigra) and rape (Brassica napus) and the various aspects of planning for the major experiments were also examined. However, as the experiment was only a preliminary investigation, neither a statistically valid design nor any statistical treatment of the data were attempted.

The soil and its treatment. About one tonne of a loam soil was taken from a field at Papple Farm, Haddington, which had been recently ploughed after being in grass for many years. At the time of sampling, which was about 24 hours after a few days of rainfall, the moisture content of the soil was 22.6% (average of 6 determinations).

On arrival in the glasshouse, the soil was cleaned of the large stones and plant roots, and was divided into three groups which were treated as follows:

Group I. Air dried, gently crushed and the aggregate size range, 0.5 - 4.8 mm, sieved out.

Group II. Spread in a thin layer (10-15 cm) on a hard flat surface, while still at the field moisture content, i.e. 22.6%, and compacted by pushing a 100 kg garden roller over it 20 times before treating as Group I.

Group III. Air dried for 24 hours, during which the moisture content fell to 16%, then treated as Group II.

Pot preparations and design. Plastic pots (12 cm top diameter and 12 cm deep with 8 holes in the bottom) and saucers (12 cm diameter) were used. A thin layer of glass wool was first placed in each pot then 500 g of soil added via a brass funnel.

For each of the three species to be tested 60 pots were used for the 3 compaction levels, 2 watering regimes, 5 samplings and 2 replicates, giving a total of 180 pots in the experiment. The pots were placed in the saucers and arranged systematically in 9 rows on 3 benches in the glasshouse.

The two watering regimes were: continuous watering and withdrawal of watering 6 weeks after sowing. The five samplings were carried out at weekly intervals from the date of watering withdrawal.

Sowing and watering. On May 9th, the saucers were filled with water and additional water was added when necessary. After 24 hours, when moisture reached the soil surface in all the pots, 10-12 seeds were sown in each pot. Emergence of clover began on May 15th and of the mustard and rape on May 16th. On May 24th, the number of the seedlings in each pot was reduced to 6 as uniform and evenly distributed as possible. As the rape seedlings were found to be uneven and rather weak, the rape was dropped at this stage from the experiment. On June 21st, the saucers were removed from the "watering withdrawal treatment" pots, so the excess water was drained and the only source of water for the plants was that which was retained by the soil. On June 28th, the first sampling was carried out.

Sampling and Dry Matter determination. Sampling of the aerial part of the plants in each pot was carried out at the weekly intervals. The samples were kept in closed polythene bags before oven drying at $90 \pm 5^{o}C$. for 24 hours and weighing.

Symbols. The following symbols were used:

CO for no compaction,

CH for compaction at high moisture content,

CL for compaction at low moisture content,

W1 for continued watering,

WO for withdrawl of watering, and

S1..to S5 for the five samplings respectively.

Laboratory determination of the percent of water holding pores. Currie's (1966) method for measuring crumb porosity was used for the determination of the percentage of the pores which hold water against 50 cm water suction. 2-4 g of crumbs (1-2mm) were placed in a fine mesh sieve and saturated with decolorized kerosene in a vacuum desiccator. The sieve was then placed on a sintered glass funnel through which 35 cm kerosene ($\approx$50 cm water) suction was applied to the crumbs for 20 minutes. The crumbs were then weighed (M), their total volume was measured (V) by displacement with kerosene, then they were oven dried at $105^{o}C$ for 24 hours and weighed again (m). The crumb porosity (E_c) was then calculated from the equation:

$$E_c = \frac{M - m}{V.p} \times 100$$

where p is the specific gravity of kerosene at the laboratory temperature.

Results. The dry matter production of the clover plants is graphically presented in Fig. 17. In the mustard plants, flowering started after the second sampling. As dry matter production is highly reduced in herbaceous plants during the flowering stage, mustard was considered as unsuitable for the experiment. Flowering in the clover plants started towards the end of the experiment, and it was considered as a suitable test plant. The results of crumb porosity determinations are tabulated in Table 1.

Table 1. Percent crumb porosity of the soil at the three compaction levels (mean of 6 determinations).

NC	CH	CL
27.3	27.5	28.5

Discussion. The basic assumption in interpreting the results is that increased available water capacity of soil results in a higher dry matter production and probably a longer period of growth under conditions when drought follows a wet period. The data of Fig.17 suggest such a beneficial effect of compacting the soil at 16% moisture content. From direct observations (PlateI) it was also noticed that 10 days after water withdrawal, the clover plants in the CO and CH pots were wilting while in the CL pots they were still turgid.

The crumb porosity determ'nations show an increase of 1.2% and 0.2% in the total volume of the water holding pores at CL and CH compaction levels respectively as compared with NC. Assuming the crumb pores are full of water, as it would be expected when equilibrated against 50 cm water suction, and assuming the actual density of the soil particles is 2.5 g cm^{-3}, the moisture content of the soil at the three compaction levels can be calculated. Such calculations show that the 1.2% increase in the crumb porosity at the CL compaction level, results in an increase of about 6.1% in its available water capacity. It is this increase in the available water capacity of the crumbs which is considered to have resulted in a higher dry matter production in the CL pots after water withdrawal.

On the other hand, neither the dry matter production nor the crumb porosity data indicate any beneficial effect of compacting the soil at 22% moisture content. In fact the dry matter production under both water regimes is reduced compared with that of the control (NC), suggesting negative effects of compaction at high moisture contents.

Conclusions leading to the planning of the major experiments. The following conclusions were made from the results of the pilot experiment and from the literature review:

1. Compacting the soil in the manner used in the pilot experiment at moisture contents near to that of its field capacity, is likely to result in an increase in its available water capacity without producing any negative effect in the physical fertility of the soil.

2. For better assessment of the effect of compaction on the water holding pores of the soil, larger aggregates should be used in order to minimize the establishment of extra micro-pores at the points of contact between the aggregates.

3. For easier detection of the stage where growth stops, i.e. the available water approaches its lower limit, the interval periods between the samplings should be made as short as possible. This point also suggests either establishing fewer plants per pot or alternatively using larger pots which accommodate more soil.

4. For a better detection of the change in the available water capacity of the soil, from the response of established plants, the use of the available water for dry matter production should be at maximum. Direct evaporation from the soil should therefore be minimized,

suggesting:

a) The experiment should be carried out under cool and humid conditions.

b) A mulch should be used, the material of which, in addition to minimizing the direct evaporation, can be selected to serve also as a seedbed which has the advantages of producing seedlings of initially similar size and vigour.

5. Clover is a suitable test plant for experiments of this nature because:

a) It reaches the flowering stage, where dry matter production is reduced after rather a long period, during which the various treatments can be carried out.

b) Being a legume, the problem of nitrogen nutrition, which is sensitive to the pore system, is less serious than with non-leguminous species.

c) It is a sensitive crop to the availability of water in the soil.

EXPERIMENT I

This was a factorial pot experiment carried out to investigate the effect of compacting the soil, with the same compactive effort at two moisture contents, on the percentage of water holding pores in the soil. The consequent effect on the increase in the available water capacity of the soil was assessed, from the growth response of clover plants, in two aggregate size ranges at two watering regimes. Samplings, in 5 replicates, were carried out at five stages of growth.

Soil. About $1\frac{1}{2}$ tonnes of clay loam were taken from a field at Papple Farm, Haddington. The field had been a permanent pasture, and hence, the soil was not expected to be highly compacted. Sampling of the soil was carried out after removing the grass turf from a 3 x 3 yard plot and digging the mineral A horizon to a depth of about 25 cm.

The soil belongs to the Beil series of the Beil association. Ragg and Futty (1967) described the A horizon of the Beil series as "reddish brown (5YR/4) clay loam, coarse blocky, plastic of low organic matter content, occasional stones and frequent roots". According to Ragg and Futty, the soils of Beil association are developed on drifts derived from lower Carboniferous Limestones, Cementstones and Shales with Upper Old Red Sandstone Marls, Sandstones and Conglomerates.

The important physical and chemical properties of the soil have been determined and are tabulated in Appendix, Table 1.

Treatments. On arrival of the soil in the glasshouse, the large stones (> 2 cm) and plant roots were removed and the soil divided into 3 groups, which were treated as follows:

Group I. Air dried and gently crushed.

Group II. Sprayed with water, thoroughly mixed and covered with a polythene sheet for 48 hours to equilibrate. Spread in a thin layer (10-15 cm) on a hard flat surface before compacting by pushing a 250 kg garden roller over it 20 times (10 times two ways). Thoroughly mixed, air dried and gently crushed, the moisture content at the time of compaction was 31% (average of 6 determinations).

Group III. Treated as group II, with the compaction treatment carried out at a lower moisture content. Before being compacted, the moistened soil allowed to air dry for 24 hours, during which it was thoroughly mixed twice. The moisture content at the time of compaction was 23% (average of 6 determinations).

From each group, two ranges of aggregate sizes, viz. (0.5-4.8 mm) and

(0.5-6.3 mm) sieved out.

Pot preparations and layout. Plastic pots (18 cm top diameter and 18 cm deep with 8 holes at the bottom) and saucers (18 cm diameter and 2.5 cm deep) were used. A thin layer of glass wool was first placed in the bottom of each pot, 750 g of coarse sand was added to raise the lowest part of the soil in the pots just above the water level in the saucers when full. The equivalent of 2 kg oven dry weight of the aggregates were added via a brass funnel. The surface of the soil was gently levelled and 250 cc (about 1 cm in thickness) of vermiculite were added and levelled on the top of the soil.

The bulk densities and porosities of the soils in the pots were determined and are tabulated in Table 2.

Table 2. Bulk density and total porosity of the soil in the pots.

		B.D.	Porosity
Aggregate range 0.5-4.8 mm	non-compacted	1.02	58.5
	compacted at 23% m.c.	1.02	58.5
	compacted at 31% m.c.	1.04	57.7
Aggregate range 0.5-6.3 mm	non-compacted	1.10	55.3
	compacted at 23% m.c.	1.11	54.9
	compacted at 31% m.c.	1.12	54.5

The sand layer was established in the pots to minimize the risk of water logging, and the vermiculite layer to serve as both a mulch to reduce direct evaporation and a seedbed to minimize the differences, associated with germination, in the initial quality of the seedlings. Watering was carried out from below to reduce the risk of damage to the aggregates and consequent alterations in the pore systems. The two watering regimes were continuous watering and withdrawal of watering 7 weeks from the date of sowing.

When preparations of the pots were completed, they were put in the saucers and arranged (plate II) in a wire cage, open to atmospheric conditions, which was covered with a polythene sheet to prevent the rain falling on the pots. However, in mid-September, because of the cold weather, they were transferred into the glasshouse. In both the wire cage and the glasshouse, a split plot design was used; the main plots being the 25 sampling units of (5 samplings x 5 replicates). These were arranged in a 5 x 5 latin square. The split plots were the 12 treatment combinations of (3 compaction levels x 2 aggregate size ranges x 2 watering regimes). These treatments were randomized within each main plot giving a total of 300 pots. The analysis of variance was later carried out collectively for the samplings data.

Sowing and watering. On August 3rd, the saucers were filled with water and kept full by adding water as necessary. On August 5th, though moisture was noticed on the surface of the soil in the pots, the vermiculite layer remained dry, therefore, all the pots were gently sprayed, and 12-15 seeds of clover were sown in the vermiculite layer. Gentle spraying was carried out twice a day. Emergence started on August 10th, and on August 11th, spraying was stopped as it was considered to be no longer necessary. On August 20th, the number of the seedlings in each pot was reduced to 6 of as nearly as possible similar qualities (vigour and size). On September 15th, the pots were transferred into the glasshouse. Watering was withdrawn from the appropriate pots on September 17th. On September 20th, the first sampling was carried out and followed by subsequent samplings at the intervals mentioned under the heading, "Symbols" (see page 87).

Sampling. Sampling of the plants was carried out by cutting all the plants in each pot at the soil surface. Moisture content of the soil in each pot was gravimetrically determined on the same day as plant sampling on about 200 g soil sampled from each pot after intimate mixing of the soil.

Symbols.

1. Compaction.

CO for no compaction,

C1 for compaction at 23% moisture content,

C2 for compaction at 31% moisture content.

2. Aggregate size ranges.

A1 for the range 0.5 - 4.8 mm,

A2 for the range 0.5 - 6.3 mm.

3. Watering regimes.

W1 for continuous watering,

WO for watering withdrawal.

4. Samplings.

S1 for the first sampling, 3 days after starting WO treatment,

S2 for the second sampling, 10 days after starting WO treatment,

S3 for the third sampling, 14 days after starting WO treatment,

S4 for the fourth sampling, 18 days after starting WO treatment,

S5 for the fifth sampling, 22 days after starting WO treatment.

EXPERIMENT II

In this factorial experiment the soil was compacted at one moisture content and aggregates of one narrow size range of compacted and non-compacted soils were used. These were packed at three density levels, giving six combinations of inter- and intra-pore systems in the pots. Clover plants were allowed to grow in the pots under two watering regimes. Samplings were carried out at six stages of growth and there were 5 replicates.

Soil. From another field in Papple Farm, Haddington, which had been under cultivation for many years, 8 tonnes of a clay loam were taken from the plough layer. The soil belongs to the previously described Beil series. Its important physical and chemical properties have been determined and are tabulated in Appendix, Table 1.

Treatments. On arrival of the soil in the glasshouse, the large stones (> 2 cm) and plant roots were removed, and the soil was divided into two groups which were treated as follows:

Group I. Air dried and gently crushed.

Group II. Spread in a thin layer (10-15 cm) and compacted at the field moisture condition which was 21%, by driving a vibrating road roller (plate III), weighing 350 kg, over it 10 times (5 times two ways) during which the compacted blocks were overturned twice. The compactive force was doubled by vibration. Air dried and gently crushed.

From each group aggregates of the size range 1.00-1.25 cm were sieved out. The aggregates were then spread out on two polythene sheets and a nutrient solution of K_2SO_4 and KH_2PO_4 was sprinkled over them in three lots with intimate mixing after each lot. The amounts of fertilizers (27.8 g K_2SO_4 and 43.9 g KH_2PO_4 in 3 litres deionized water per ½ tonne soil) were calculated to apply P and K at rates equivalent to 20 and 50 mg Kg^{-1} respectively. The two watering regimes were the same as those of experiment I.

Pot preparation and packing. The same pots and saucers as for experiment I were used and the same pre-filling preparations were made before packing the equivalent of 2.5 kg dry weight of the aggregates in each pot. The three density levels were obtained by packing as follows:

1. Open packing: The aggregates were added via a brass funnel.

2. Close packing: After adding the aggregates as in "open packing", the pots were put on a vibrating plate (Plate IV) which was then operated till settlement was achieved.

3. Packing with sand: The aggregates added in 2-3 cm layers, the space in between them filled with sand of 1.2-1.7 mm grain size range. 1 kg of sand was used per pot and care was taken to produce uniform distribution of the sand grains in between the aggregates.

The bulk densities and porosities of the soils in the open and close packing pots and of the soil-sand mixture in the other pots were determined and are tabulated in Table 3.

Table 3. Bulk density and porosity of the soil in the pots at the two levels of compaction and the three levels of packing.

Treatments		Bulk density $g\ cm^{-3}$	Porosity % v/v
open packing PO	non-compacted	1.15	54.7
	compacted	1.16	54.3
close packing PC	non-compacted	1.25	50.8
	compacted	1.29	49.2
Packing with sand* PS	non-compacted	1.50 including sand	42.9
		1.07 excluding sand	57.9
	compacted	1.57 including sand	41.5
		1.09 excluding sand	57.1

* Specific gravity of sand is 2.8.

On completion of packing, the surface of the soil in the pots was levelled, 250 g of a medium grade Finn peat added to the surface and levelled giving a thickness of 1-2 cm mulch.

Layout of the pots. When preparation of the pots was completed, they were put in the saucers and arranged in the glasshouse (Plate V) in a split plot design, the main plots being the 30 sampling units of 6 samplings x 5 replicates. The 6 samplings were randomized in 5 replicate rows. The split plots were the 12 treatment combinations of : 2 compaction levels x 3 packings x 2 watering regimes. These treatments were randomized within each main plot giving a total of 360 pots in the experiment.

Sowing, Watering and Sampling. These were carried out in the same way as in experiment I at the following dates:

10 May. Saucers filled with water,

15 May. Gentle spraying started and 12-15 seeds of clover per pot sown,

20 May. Emergence started,

21 May. Spraying stopped,

29 May. First thinning to 8 seedling per pot carried out,

3 June. Final thinning to 6 seedlings per pot carried out,

29 June. Watering stopped on the appropriate pots, first sampling carried out and followed by the subsequent samplings at the dates mentioned under the heading "Symbols".

Symbols.

1. Compaction.

Co for no compaction,

C1 for compaction.

2. Packings.

PO for open packing,

PC for close packing,

PS for packing with sand.

3. Watering regimes.

W1 for continuous watering,

WO for watering withdrawal.

4. Samplings.

S1 for first sampling at the same day of WO treatment,

S2 for second sampling 6 days after WO treatment,

S3 for third sampling 9 days after WO treatment,

S4 for fourth sampling 12 days after WO treatment,

S5 for fifth sampling 15 days after WO treatment,

S6 for sixth sampling 21 days after WO treatment.

A change in the design. As the expected differences in growth at the second sampling were not apparent and as the soil moisture characteristic curves showed little difference between the two levels of compaction, a slight modification was made to the design. Sixty pots of continuous watering treatment (samplings 3 and 5) were subdivided into two groups and water withdrawn. In group I, water was added when 10% wilting occurred, and in group II, water was added at 50% wilting, i.e. when wilting was noticed in about 10% of the plants in the former case and in about 50% of the plants in the latter case. Once full recovery of all plants took place, the cycle was repeated twice, then sampling was carried out.

EXPERIMENT III

This factorial experiment was a refinement of the previous two experiments. Clover plants were grown in compacted and non-compacted soils of two discrete aggregate size ranges. Two watering regimes were included and samplings, in 4 replicates, were carried out at five stages of growth.

The watering regimes were imposed by the use of 4 large sand tanks specially constructed for the purpose of accurately applying, to groups of pots, tensions in the range 0 to 100 cm water for the desired periods. Special pots were also made and both the sand tanks and the pots will be described before giving the details of the design of the experiment.

The sand tanks

In principal, the sand tanks were similar to the Dutch-designed sandbox apparatus (Harst and Stakman, 1965) with considerable modifications required to suit the purpose of the experiment (Plate VI).

The tanks. The tanks were made locally (Balfour and Kilpatrick Ltd., Edinburgh) to my specification. The dimensions of a tank and the locations of four fitted outlets for the drains are illustrated in Fig. 18,a. To ensure complete rigidity 1/8" gauge aluminium plate was used and the upper 1.5 cm of the sides were folded inwards and welded at the seams to give increased mechanical strength.

<u>The drains.</u> Drainage of each tank was provided by 4 sets of nylon tubing grids (Fig. 18,b) attached to the four drain outflows. The nylon tubing ($\frac{1}{4}$" o.d.) was perforated on the underside at 1 cm intervals by holes of approximately 0.5 mm in diameter and was wrapped with several layers of a fine mesh nylon to exclude silt and fine sand. To ensure that all air bubbles could be easily removed from the drains, the outflows were made at the highest points in the drain system. The four outflows were connected outside each tank by means of plastic T pieces and nylon tubing to a manifold which in turn was connected through a 3-way stopcock to a main drain, through which the desired tensions were applied, and to a main water reservoir, from which the tanks were reflooded. A bubble tube was inserted into the water reservoir and adjusted at a height sufficient to ensure that the hydraulic head did not exceed 2-3 cm above the sand surface in the tanks.

<u>The supports.</u> As calculations showed that the weight of each tank in operation would be about one tonne, very strong support was required. This was constructed from four heavy duty glasshouse benches together with eight 10 x 10 cm cross section and 2 m long timbers, in such a fashion to give 1.5 m clearance between the sand surface in the tanks and the glasshouse floor. This clearance was required for creating tensions up to 100 cm water.

The tanks were placed and levelled on the support in two pairs with 30 cm between the long sides and 80 cm between the short sides of the tanks. In the central space the main water reservoir and a special vertical wooden rod with a groove to accommodate the manometers of the tensiometers (dealt with later) were placed. The manifolds of the tanks were fixed on either side of the support.

The sand. Calculations and preliminary laboratory tests had shown that the sand necessary for holding the maximum tension required (100 cm water) in the tanks had to be not less than 7 cm in thickness and to have at least 80% of its particles within the range 30-70 microns and with no particles greater than 150 or finer than 10 microns. Coarser sands failed to retain the maximum required tension. Finer sands drained too slowly.

Considerable difficulty was encountered in acquiring such a sand from normal commercial sources and eventually it was necessary to resort to taking and testing samples from the settling lagoon of several local sand-pits.

About 1.5 tonnes of the specific sand was, as calculated, necessary for the four tanks. This was finally obtained by sedimentation and wet sieving from five tonnes of a very fine sand collected from the settling lagoon of one of local sand pits which the test showed to be suitable.

To prevent the fine sand being washed into the drainage tubes of the tanks, two layers of coarse sand were used as filters. The lower layer, completely covering the drain tubes, was on average 2.5 cm thick and comprised sand particles in the range 1 to 5 mm in diameter. The other layer, also about 2.5 cm thick, consisted of sand with a particle size range of 0.5 to 1.0 mm in diameter. To exclude air from the system the tanks were half filled with water before adding the sand filter in thin layers. A layer, about 10 cm thick, of the main bulk of sand was built up in thin layers on the filter sand by addition in the form of a thin slurry. Excess water was continuously removed through the drainage system. Filling of each tank took one man about 8 hours work.

Four tensiometers were constructed according to Webster (1966), the cup of each was embedded in the fine sand layer of a tank. The mercury reservoir of the tensiometers was placed in the groove of the wooden rod at the same level as that of the surface of the sand in the tanks. Readings of the tensiometers were later used for checking the established tensions in the tanks and in the soils in the pots, corrections being made to the mid-height of the soil columns in the pots.

To remove entrapped air from the system, the tanks were flooded with water and a tension of about 150 cm water (11 cm mercury) was applied by means of a water pump connected to the free end of the main outflows. This caused a steady flow of water through the system. Additional water was continuously added to the surface to maintain a minimum depth of 2 cm water. This flushing process continued until air bubbles ceased to appear in the effluent. The ends of the main drains were then submerged in water in a large container which could be raised or lowered as necessary to give the desired tensions. These containers were kept full of water.

To minimize direct evaporation from the sand surfaces, four close fitting wooden lids were made for the tanks and painted with a waterproof material. In each lid, five rows of eight holes (11 cm diameter) were cut to enable the cylindrical pots to be placed directly on the sand. Wooden bars, 5 x 5 cm cross section, were fixed between the rows of the holes in such a manner that on raising and turning the pots through 90°, they supported the pots by means of their lugs (see below) at about 5 cm above the sand surface.

The pots

These were made by stretching fine nylon mesh across the base of plastic tubes (trade name "Metrex"), 10.2 cm inner diameter and 15 cm high. The nylon mesh was maintained firmly in position by means of copper wire tightly bound in a retaining groove previously made at a distance of 5 mm from the base of the tubes. To ensure very uniform contact with the sand, the bases of the pots were precision turned in a lathe. Two curved lugs, 3 cm long, were cemented on either side of the pots at a height of 10 cm to enable the pots to be supported on the lids above the sand surface.

Soil. Prior to collecting the soil from Beil Farm, Haddington, samples were taken from a field in an arable rotation and from a recently cleared deciduous shelterbelt. Analyses performed on both soils showed a more favourable pore system in the latter and it was therefore, considered more suitable for the purpose of the experiment. Consequently, 2 tonnes of soil, a clay loam, were taken from the mineral A horizon of the area under the shelterbelt. The soil belongs to the previously described Beil series (see Page 84). Its important physical and chemical properties are tabulated in Appendix, Table I.

Treatments. The pre-compaction treatments of the soil were similar to those performed on the soils of experiments I and II. In the glasshouse, the soil was divided into two groups which were treated as follows:

Group I. Air dried and gently crushed.

Group II. Sprayed with water, thoroughly mixed and covered with a polythene sheet to equilibrate for 48 hours. Spread in a thin layer (10-15 cm) on a hard flat surface, covered with a plastic sheet and compacted by pushing a 350 kg vibrating road roller (Plate VII) over it 10 times (5 times 2 ways) with the soil blocks being overturned twice during compaction. Air dried and gently crushed. The moisture content of the soil at the time of compaction was 27% (average of 6 determinations).

From each group two aggregate size ranges: (0.5-4.8 mm) and (4.8-9.5 mm) were sieved out.

Pot preparations. The equivalent of 1 kg dry weight of aggregates were added, via a brass funnel, to the pots. The surface of the soil levelled and 80 g of a medium grade Finn peat was added on the surface and levelled giving a thickness of 1-2 cm mulch.

The bulk densities and porosities of the soil in the pots were determined and are tabulated in Table 4:-

Table 4. Bulk density and porosity of the soils in the pits.

		Bulk density	Porosity
Aggregate range 0.5-4.8	non-compacted	0.86	65.5
	compacted	0.87	65.1
Aggregate range 4.8-9.5	non-compacted	0.85	65.9
	compacted	0.86	65.5

Sowing and initial watering. When preparations of the pots were completed, they were placed in 12 cm top diameter plastic saucers which were kept full of water until the pots were transferred onto the sand tanks. 10-12 seeds of clover were sown in the peat layer of each pot and the pots were gently sprayed. Gentle spraying continued twice a day until emergence started. Thinning, first to 6 then to 4 seedlings per pot, was carried out in the same manner as in the previous experiments. The pots were then transferred onto the tanks. The dates of these operations are included in the growing-season time-table which follows.

Layout of the pots on the sand tanks. For arrangement of the pots on the tanks a split plot design was used: the main plots (one tank) being one of the two replicates of each watering regime for which two diagonally opposite tanks were used. Each main plot was subdivided into 5 sampling units (one row of 8 pots in a tank). Each sampling unit contained 2 replicates of the factorial combinations of 2 compaction levels x 2 aggregate sizes. These were randomized separately for each sampling unit and the 5 sampling units were randomized separately for each main plot, giving 40 pots on each tank and a total of 160 pots in the experiment.

The two watering regimes. When the layout of the pots on the sand tanks was completed, the main drains were opened to the water reservoir in order to maintain a minimum depth of 1 cm water on the sand surfaces. The plants were allowed to grow thus for a period of 4 weeks. The two watering regimes were then imposed by applying, through the sand tanks, 7 successive cycles of stress and rewatering. In each cycle the following were carried out:

1. Applying to the appropriate tanks, tensions of 50 cm water (low stress) and 100 cm water (high stress) for 48 hours, by having the pots placed on the sand surface in the tanks. The tensions were applied by having the water table in the containers, where the main drains were submerged, at depths of 50 and 100 cm from the mid-height of the pots. The created tensions were checked twice daily from the tensiometer readings.

2. The pots were lifted up and supported on the wooden bars of the lids. The tension in the tanks was reduced to 2-3 centimetres of water. The plants in this stage were dependent on the water retained by the soils during the 48 hours tension. This stage continued until wilting was apparent on 50% of the pots in the whole experiment.

3. The pots were replaced on the sand surface and watering carried out as before, occasionally the pots were gently sprayed to ensure that the moisture content of the soils approached saturation before starting the next cycle.

During stage 2 of the fifth and sixth cycles, the pots were taken out and the roots which had passed through the nylon mesh of the pots were trimmed.

The dates when these cycles were carried out, are given in the growing season time-table.

Sampling. Sampling of the plants was carried out in the same manner as in the previous experiments. Samplings 1, 2, 3 and 4 were carried out 24 hours after rewatering in cycles 3, 4, 5 and 6, when the plants recovered from wilting. Sampling 5 was carried out when wilting reached the 50% level in the second stage of cycle 7. Therefore, the fresh matter weights of the plants in the fifth sampling are those of the wilting stage.

Growing season time-table.

March	21	Saucers filled with water.
March	23	Sowing and gentle spraying.
March	29	Emergence started and gentle spraying stopped.
April	6	First thinning to 6 seedlings per pot.
April	13	Final thinning to 4 seedlings per pot.
April	16	The pots transferred on the sand tanks.
May	12	First cycle started with rewatering on May 21.
May	25	Second cycle started with rewatering on May 31.
June	14	Third cycle started with rewatering on June 10.
June	11	First sampling carried out.
June	13	Fourth cycle started with rewatering on June 18.
June	19	Second sampling carried out.
June	21	Fifth cycle started with rewatering on June 26.
June	27	Third sampling carried out.
June	30	Sixth cycle started with rewatering on July 3.
July	4	Fourth sampling carried out.

July 6 Seventh cycle started (first and second stages only).

July 9 Fifth sampling carried out.

Symbols.

1. Compaction.

CO for no compaction

C1 for compaction.

2. Aggregate size.

A1 for aggregate size range (0.5-4.8 mm)

A2 for aggregate size range (4.8-9.5 mm)

3. Watering regimes.

T50 for 50 cm tension (low stress).

T100 for 100 cm tension (High stress).

A supplementary experiment. For assessing the effect of compaction in the two aggregate size ranges, on growth of clover when the stress is limited to that which results from the height of the soil columns above the water table, a supplementary experiment was carried out in the same glasshouse and at the same time. In this experiment 16 pots (2 compaction levels x 2 aggregate sizes x 4 replicates) identical to those of the main experiment were used. The pots were placed in 12 cm top diameter saucers and randomized in a 4 x 4 latin square. The saucers were kept full of water until sampling of the plants was carried out at the same day as the last sampling of the main experiment.

B. Analytical Methods

1. Soil Analysis

Preparation of soil samples. Soil samples collected for laboratory work were placed in trays in a heated room (25-30^{o}C) until dry. The samples were ground, passed through a 2 mm sieve and stored in paper bags until required.

Field bulk density determination. From the same fields where the soils were collected for the experimental work, cores of soil were taken in cylindrical tins of an internal volume of 222 cm^3 driven into the points concerned using the sampler by Dagg and Hosegood (1962).

As these cores were also used for the field moisture content determinations, the tins were fitted with lids to prevent evaporation. In the laboratory the lids were removed and the cores weighed, correction being made for the weight of the tins. The cores were then dried at 105°C for 48 hours in a forced-draught oven and weighed again.

The dry weight of the core was used for calculating bulk density as g oven dry soil cm^{-3}.

Field moisture content determination. The loss in weight on oven drying of the cores sampled for bulk density determination was used for determining the moisture content of the soils at the time of collection for the experimental work. Unless otherwise stated, the soil moisture is always expressed as g moisture per 100 g oven dry soil.

Determination of bulk density in the pots. The only unknown values for bulk density determinations on a weight/volume basis were the soil volume height x cross sectional area in the pots.

The height was calculated for each treatment in 10 random pots by measuring and averaging the distance between the soil surface and the upper edge of the pots (Plate VIII) at three random points. These were subtracted from the distance between the surface of the sand layer below the soil, already measured, and the upper edge of the pots in experiments I and II, and from the height of the pots in experiment III. Height measurements were always carried out when the soil, after the first sampling was saturated and hence settled.

The cross sectional areas, in case of experiments I and II, were calculated at mid-height of the soils in the pots.

The calculated bulk densities were expressed as g oven dry soil cm^{-3}.

<u>Determination of particle density.</u> The particle density was determined on the 2 mm fraction samples prepared for chemical analysis, using 50 ml specific gravity bottles according to a method described by Blake (1965) but using kerosene instead of distilled water. The density of kerosene was determined using the same bottles. The particle density was expressed as g cm^{-3}.

<u>Determination of total porosity.</u> The total porosities of the soils both in the field and in the pots were calculated from bulk density and particle density data using the formula:

$$\text{porosity} = (1 - \frac{\text{bulk density}}{\text{particle density}}) \times 100.$$

The total porosities are expressed in volume/volume basis.

<u>Determination of soil moisture characteristic curves.</u> Soil moisture contents of the various aggregate-size ranges used in the experiments, were determined in the range - pF 1.0 to pF 4.2.

During placing the soil samples in the various systems used for these determinations, which will be discussed later, care was taken to simulate the same degree of packing as that in the pots except for close packing and packing with sand of experiment II, which were difficult to simulate in the systems.

Moisture contents in the range up to pF 2.0 were determined using Clement's (1966) tension table for the soils of experiments I and II. For the soils of experiment III, the previously described sand tanks were used. A 30 x 50 cm piece of filter paper was first placed on the sand surface in a tank on which a number of rubber rings, about 5 cm in diameter and 1 cm deep, were placed and about 25 g of aggregates were added to the rings. The main drain of the tank was opened to the water reservoir and the aggregates were flooded for at least 48 hours after which the desired tension was applied for another 48 hours, during which the tank was completely covered by a lid. Previous tests had shown that a period of 48 hours would be sufficient for equilibration. The moisture contents of samples of the aggregates were then gravimetrically determined and expressed in g moisture per 100 g oven dry soil.

For the pF range 2.5-3.5 inclusive, "3 bar" and for the pF range 3.7-4.2 inclusive, "15 bar" Ceramic Plate Extractors (Soil Moisture Equipment Company, Santa Barbara, California, U.S.A.) were used according to Richards (1965). The aggregates were allowed to stand, in the rubber rings with an excess of water on the plates, for a period of at least 4 days before placing the plates in the pressure chamber. After equilibration in the pressure chamber against the applied tensions, which took periods ranging from 7 to 12 days, the moisture content of the soils was determined as before.

The moisture characteristic curves were drawn by plotting the moisture contents at various tensions versus the tension values expressed both as pF.

<u>Determination of water and air capacities.</u> The water capacity of the soil in the pots was calculated on the v/v basis as follows:

In a unit volume of soil:

$$\text{the total pore volume} = 1 - \frac{P_b}{P_p}, \quad \text{------------------} \quad \text{I}$$

and

$$\text{the volume of water} = \Theta_m \cdot \frac{P_b}{P_w} \quad \text{------------------} \quad \text{II}$$

where, P_b is the dry bulk density of the soil, P_p is the particle density,

θ_m is the water content by mass of oven dry soil (the values of which were obtained from the pF curves) and P_w is the density of water.

Then assuming the density of water is 1 g cm^{-3}, and subtracting the right side of equation II from that of equation I, the air capacity as percentage of the total volume can be obtained from the equation III.

$$\text{air capacity} = [(1\frac{P_b}{P_p}) - (\theta_m \times P_b)] \times 100 \text{ ---------------} \qquad \text{III}$$

In experiment II, the reduction in total porosity by close packing (PC) and packing with sand (PS) was considered to be mainly in the macro-pores.

In close packing (PC) the calculation of air capacity at different moisture contents, was carried out according to equation III, and the loss in the percentage of macro-pores is represented in Fig. 36. In packing with sand, as the volume of soil-sand mixture in the pots was slightly more than that of the soil in open packing, the potential total porosity in between the soil aggregates was about 5% higher than in open packing, but about 50% of the macro-pores were filled with solid sand. The calculation of air capacity of the soil was carried out again according to equation III and the fraction of the macro-pores filled with sand is also calculated (Fig. 36).

Aggregate stability. The instability test of aggregates of Williams and Cooke (1961), which is based on loss in pore space on slacking was used.

The apparatus consists of a graduated glass tube (13 mm inner diameter and 40 cm long) closed at the lower end by a square of muslim over a rubber stopper penetrated by a glass tube connected by nylon tubing to a manometer. The manometer is kept full of water, hence by raising or lowering, the water level in the glass tube can be adjusted.

30 g of air-dried aggregate (4-6 mm) were placed in the glass tube and tapped gently to pack the dry aggregates before measuring the soil height and calculating the volume of column of dry aggregates (Z). Water was then admitted by raising the manometer gently to avoid trapping air bubbles between

the aggregates until there was 1 cm water above the soil column. After standing for 10 minutes the water was drained completely by lowering the manometer. The procedure was repeated until the soil column was settled, i.e. constant height, and the volume was measured again (y). The instability factor was then calculated = [(Z-Y)/(Z-X)] x 100, where X is the absolute volume of the soil calculated from its dry weight and particle density. In their work, Williams and Cooke considered the instability factor 0 as completely stable, 5 highly stable and > 10 unstable.

Pore-size distribution determination. Various pore-size classes were determined as fractions (in percentage) of the total volume of pores using a conversion table by Kirkham and Powers (1972) which is based on the capillary rise formula.

Determination of particle-size distribution. Mechanical analysis was carried out using the pipette method described by Kilmer and Alexander (1949), and particles separated according to I.S.S.S. limits.

Determination of organic matter content. Organic carbon was determined by the modified Tinsley method (Bremner and Jenkinson, 1960) using 0.5 g soil ground to pass through a 0.2 mm sieve. The obtained values were converted, by multiplying by the factor 1.74, to organic matter content expressed as percentage of oven dry soil.

Determination of soil reaction. Soil pH was measured in a 1:2.5 suspension of soil and water on a Pye pH meter using a glass electrode and calomel half cell.

Extraction of "available P" and "available K". Soil extracts were obtained using a modified Morgan's reagent (pH 4.5) as described by Hende *et al* (1953).

Determination of "available P" and "available K". The extracts were analysed for "available P" by measuring the intensity of the blue colour produced with ammonium phosphomolybdate after reduction by $SnCl_2$, using the method described by Alston (1964).

"Available K" was determined on the soil extract using the flame photometer method (Collins and Polkinhorne, 1952).

Determination of cation exchange capacity. The cation exchange capacity was determined by NH_4^+ saturation of the soil and displacement by NaCl (Chapman, 1965). The NH_4^+ was determined by distilling the NaCl leachate in a Kjeldahl distillation apparatus, using MgO, into boric acid (H_3BO_3) containing mixed indicator. When distillation was complete the distillate was titrated against 0.1N HCl.

2. Plant Analysis

Dry matter determination and preparation for analysis. The plant material was dried overnight in a forced draught oven at 90°C. The dry matter content was determined by weighing.

The whole sample was ground in a mill and stored in poly-pots until required for analysis. Prior to analysis all samples were dried at 105°C.

Digestion of plant material for the determination of N, P, K, Na, Ca and Mg

The method used was a modified method of O'Neill and Webb (1970), using a digestion solution of 0.35 per cent Selenium in conc. H_2SO_4. 4 ml of this solution was added to 250 mg of plant material and heated gently for 10-15 minutes and allowed to cool. 2 ml of 30% H_2O_2 were then added and the solution digested vigorously until solution had cleared. Digestion was continued for 1 hour. After cooling the digest was diluted with de-ionized water to make a volume of 50 ml.

Determination of individual elements.

Ca and Mg	by atomic absorbtion using Lanthanum diluent.
Na and K	by flame photometer using Lithium diluent.
N	by spectrophotometer, using Cyanurate/Salicylate reagent (Crooke and Simpson, 1971).
P	by spectrophotometer, using Vanadate/Molybdate reagent (O'Neill and Webb, 1970).

RESULTS

The results of each of the three experiments are reported in a manner shown schematically below.

A schematic representation of results

Soil compaction

↓

alters the following physical properties

↓

soil-water relationships	aeration	soil-thermal properties	nutrient status	strength

soil-water relationships → investigated → results to show the variations ↕ results to show differences in the yield which are related to the variation in soil-water relationships

aeration, soil-thermal properties, nutrient status, strength → controlled → results to show the control

The results (mean values only) are tabulated in the Appendices. Those results which are directly important in the discussion are reported in the text and, when necessary, presented either as tables or as graphs and histograms. Their statistical significance, as determined by analysis of variance ('F' and 't' tests) is shown by means of asterisks as follows:

*** significantly different at p 0.001.

** significantly different at p 0.01 but not at p 0.001.

* significantly different at p 0.05 but not at p 0.01.

An example of the analysis of variance is presented in Appendix, Table 2.

ns not significantly different at p 0.05.

However, the effects of variations in both the thermal properties of the soil and mechanical impedance have not been studied.

The effect of the thermal properties of the soil was considered negligible as the experiments were carried out in pots of relatively small size and in a glasshouse in which the daily variation in temperature was rather small.

Although the extraction of the root systems was attempted, the results were not satisfactory (1) because of the heavy nature of the soils used in the experiments, most of the root hairs were lost during extraction and furthermore, a complete separation of the whole root system was not possible, (2) because of the relatively small size of the root systems, even slight losses showed differences which could not be considered as negligible.

Nevertheless, after each sampling of the aerial parts of the plants careful visual observations were made (Plates VIII, from experiment II). Such observations showed no apparent differences in the manner of root ramification within the same sampling and watering regime and showed considerable similarities in the way the root hairs penetrated the aggregates of different compaction levels. On the other hand, root ramification was not expected to be restricted in the systems used as they could easily develop at least between the aggregates. Therefore, numerical data on mechanical impedance are not provided.

EXPERIMENT I

Soil water relationships

Soil moisture characteristic curves (Appendix, Table 3). The effects of the two levels of compaction on the soil moisture characteristic curve (mean of 6 determinations at each pF) are presented in Fig. 19 for the small aggregate size range, 0.5 - 4.8 mm (A1) and in Fig. 20 for the large aggregate size range, 0.5 - 6.3 mm (A2) with the least significant differences.

The C1 level of compaction resulted in marked increases in the moisture content of the soil at low tensions. Increases were highly significant (***) at all pF values up to 2.5 in the small aggregate size range (A1) and less significant in the large aggregate size range (A2). For both aggregate size ranges slight decreases were recorded at pF 4.2.

Effects of the C2 level of compaction were similar to those of C1 but increases of moisture content at low tensions were smaller and decreases at high tensions were greater than for C1.

Pore-size distribution. The effects of the two levels of compaction on pore size distribution of the soil in the pots are presented in Fig. 21 for the two aggregate size ranges.

The C1 level of compaction resulted in decreases (percentage of total porosity) in both the pores > 300 μm in diameter, which are drained of their water at pF 1.0 and the pores < 0.2 μm in diameter, which are retaining the unavailable water at pF 4.2 in both aggregate size ranges. These decreases in the percentages of the pores which hold excess and unavailable water, in fact, resulted in appreciable increases in the percentage of the pores in the range 0.2 - 300 μm diameter, which hold water in the available range in both aggregate size ranges. These increases were from 32.7 to 39.9% in the small aggregate size range (A1) and from 38.4% to 40.8%, in the large aggregate size range (A2).

The C2 level of compaction also resulted in similar but less marked alterations, than C1, in pore size distribution in the small aggregate size range (A1). In the large aggregate size range (A2), the C2 level of compaction resulted in a slight decrease in the percentage of the pores < 0.2 μm in diameter, but as the percentage of the pores $>$ 300 μm in diameter proportionally increased, there was no marked effect on the percentage of the pores which hold the available water.

Available water capacity. The increases in the percentage of the available-water holding pores, showed marked increases, especially by the C1 level of compaction, in the available water capacity (AWC) of the soil despite the slight decreases in the total porosity.

The effects of compaction on AWC were studied by two methods;

Method I. The AWC of the soils of the 6 treatment combinations of 3 compaction levels x 2 aggregate size ranges, were calculated as the differences in the moisture contents between the first and the third samplings. The first sampling was carried out 3 days after watering withdrawal (WO), and the moisture contents of the soils were assumed to be near to those of the upper limits. At the third sampling, according to the growth curves (Fig. 31), wilting was considered to have reached a significant stage, and therefore, the moisture contents of the soils were assumed to be near to those of the lower limits of the available water.

Such calculations (Table 5) showed that with the C1 compaction treatment, the AWC had increased by 26.1% in the small aggregate-size range (A1) and by 2.8% in the large aggregate-size range (A2) compared with the non-compacted (CO) soil. The corresponding increases in the AWC with the C2 compaction treatment were 23.8% and 14.0% respectively.

Table 5. The available water capacities of the soils as calculated from the moisture contents at samplings 1 and 3.

soil		% moisture content S1	% moisture content S3	AWC g/100g	AWC as % of AWC of CO
CO	A1	37.8	20.6	17.2	-
	A2	37.4	19.5	17.9	-
C1	A1	40.9	19.2	21.7	126.1
	A2	38.7	20.3	18.4	102.8
C2	A1	40.6	19.3	21.3	123.8
	A2	38.5	18.1	20.4	114.0

Method II. The AWC of the soils were calculated from the soil moisture characteristic curves, (Table 6) assuming the moisture content at pF 1 as the upper limit and that at pF 4.2 as the lower limit. According to this method the C1 compaction treatment increased the AWC in the small aggregate size range (A1) by 22.7% and in the large aggregate size range by 5.8%, compared with the non-compacted (CO) soil. The C2 compaction treatment increased the AWC in the small aggregate size range by 15.4% but showed no increase in the large aggregate size range (A2).

Table 6. The available water capacities of the soils as calculated from the soil moisture characteristic curves, pF 1-4.2.

Soil		% moisture content pF 1	% moisture content pF 4.2	AWC g/100g	AWC as % of AWC of CO
CO	A1	39.4	20.0	19.4	-
	A2	42.6	19.2	23.4	-
C1	A1	43.1	19.3	23.8	122.7
	A2	43.5	18.8	24.7	105.6
C2	A1	41.2	18.8	22.4	115.4
	A2	41.9	18.6	23.3	99.6

Available water at specific tensions (Fig. 22). At specific tensions, the available water was calculated as the difference between the moisture content at the particular tension and the lower limit from the soil moisture characteristic curves. The results, again expressed as percentage of AWC of the non-compacted (CO) soil show that, at low tensions, when the water is easily available for use by plants, the increase in the availability is proportionally higher than at higher tensions.

Aeration

The air capacities of the soils in the pots at various tensions are presented in Fig. 23.

Although the data show that both compaction treatments had reduced the air capacities of the soils in both aggregate-size ranges, especially at low tensions, only in the large aggregate-size range and then only at pF 1, are the air capacities in the three soils (8.4% in

Co, 6.7% in C1 and 7.4% in C2) less than the minimum value of 10% which has been shown in the literature review to be critical for plant growth.

Nutrient concentration

The effects of the compaction treatments, aggregate size ranges and watering regimes on the concentration, in the dry matter, of the nutrient elements N, P, K, Na, Ca and Mg are presented, with their "least significance" differences, in figures 24 - 29 respectively. The data are for samplings 2, 3, 4 and 5. Sampling 1 was not included as the dry matter produced was not enough for the chemical analyses procedures. The statistical analyses were carried out on the 4 samplings. The data in figures 24 - 29 are, therefore, the means of the 4 samplings only.

Within individual samplings, watering regimes and aggregate size ranges, the levels of significance of the effects of the two compaction treatments, C1 and C2, as compared with the non-compacted soil CO, are presented, for the 6 nutrient elements, in Table 7.

Table 7. The effects of C1 and C2 levels of compaction on nutrient concentration in dry matter.

			N		P		K		Na		Ca		Mg	
			C1	C2	C1	C2	C1	C2	C1	C2	C1	C2	C1	C2
S2	WO	A1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	**
		A2	*	**	ns	ns	ns	ns	**	**	*	ns	**	***
	W1	A1	ns	ns	**	*	ns	ns	ns	ns	ns	ns	*	ns
		A2	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	***	**
S3	WO	A1	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
		A2	ns	ns	ns	ns	ns	ns	*	*	ns	ns	**	**
	W1	A1	***	**	ns	ns	ns	ns	ns	ns	ns	ns	**	ns
		A2	*	**	ns	**	**	**	ns	ns	ns	ns	ns	**
S4	WO	A1	*	*	**	ns	ns	ns	ns	ns	ns	ns	ns	ns
		A2	ns	ns	ns	ns	ns	*	**	***	ns	ns	**	**
	W1	A1	ns	ns	*	ns	*	ns	ns	ns	ns	ns	*	***
		A2	ns	ns	**	**	ns	*	*	**	*	**	**	***
S5	WO	A1	ns	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	*
		A2	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	**	ns
	W1	A1	ns	ns	**	**	ns	*	ns	ns	**	ns	**	*
		A2	ns	ns	*	*	ns	ns	*	ns	ns	ns	*	ns

Nitrogen (Appendix, Table 5).

Mean of samplings. (Fig. 24,a) N concentration did not respond significantly to either of the two compaction levels C1 and C2. The aggregate-size range showed a significant (*) main effect which resulted in a lower N concentration in the narrow aggregate-size range (A1) as compared with the large aggregate-size range (A2). The main effect of the watering regime was also significant (***) on N concentration in dry matter, being higher under continuous watering regime (W1) than under watering withdrawal regime (WO). There were no significant interactions between compaction and the aggregate-size range or the watering regime.

At individual samplings (Fig. 24,b). Under continuous watering (W1) the only significant effects (**) of both levels of compaction were at S3 where N concentration was markedly increased by both compaction treatments, increases, of the order of 0.5 - 0.7 being achieved for a central value of approximately 3.5% N. In contrast, under watering withdrawal regime (WO), compaction tended to reduce N concentration at early samplings and to increase it slightly at later samplings.

Phosphorus (Appendix, Table 6)

Mean of samplings. (Fig. 25,a) P concentration showed no significant response to either C1 or C2 compaction levels, neither did it respond significantly to the aggregate-size range, but showed a significant (***) main effect of watering regime being higher when watering was continuous (W1) than when it was withdrawn (WO). There was no significant interaction between compaction and aggregate-size range, but a significant interaction (**) existed between compaction and watering regime, taking the form of decreases in P concentration as a result of compaction under continuous watering (W1) but either no effect or increases, by compaction, when watering was withdrawn.

At individual samplings (Fig. 26,b) When watering was withdrawn there were no marked effects of compaction on P concentration in dry matter at any sampling in the large aggregate size range (A2), but in the narrow aggregate size range (A1), P concentration was increased significantly by the C2 level of compaction at S3 (*) and by the C1 level of compaction at S4 (**). When watering was continuous (W1) compaction (both levels) increased the concentration of P in dry matter slightly (ns) at S1 irrespective of the aggregate size range, but depressed it at later samplings. Significant reductions (* or **) were recorded at S3 in the large aggregate size range (A2) by the C2 level of compaction and at S4 and S5 in both aggregate size ranges by C1 and C2 levels of compaction. It was a combination of these results that gave rise to the compaction-watering regime mentioned in "the mean of samplings".

Potassium (Appendix, Table 7)

Mean of samplings (Fig. 26,a) K concentration also showed no significant effects of either C1 or C2 levels of compaction or of the aggregate size range, but showed a significant main effect (***) of the watering regime, being higher when watering was continued (W1) than when it was withdrawn (W0). There was no significant interaction between compaction and watering regime, but a significant interaction (**) existed between compaction and the aggregate-size range. K concentration being slightly reduced by C1 and significantly (*) reduced by C2 levels of compaction in the narrow aggregate size range (A1), but being significantly increased by both C1 (*) and C2 (**) levels of compaction in the large aggregate size range (A2).

At individual samplings (Fig. 26,b) Effects of compaction were small under watering withdrawal (W0), except a slight increase by C1 and a significant increase (*) by C2 in K concentration in the large aggregate size range (A2) at S4, the aggregate size range compaction interaction, mentioned above, occuring mainly when watering was continuous (W1).

Sodium (Appendix, Table 8)

Mean of samplings (Fig. 27, a) Standard errors were high. Taking the means of the two aggregate size ranges and the two watering regimes the C2 level of compaction showed a significant reduction in Na concentration (**), but the reduction by the C1 level of compaction was less significant (*). There were no significant main effects, or interactions with compaction, of either the aggregate-size range or the watering regime.

At individual samplings (Fig. 27,b) There was no easily understood pattern of values except that, irrespective of watering regime, the C1 level of compaction significantly (***) decreased Na concentration at S4 in the large aggregate size range (A2).

Calcium (Appendix, Table 9)

Mean of samplings (Fig. 28,a) Ca concentration in dry matter showed significant (***) decreases resulting from the main effects of both levels of compaction. Neither the aggregate-size range nor the watering regime showed a significant main effect or an interaction with compaction.

At individual samplings (Fig. 28,b) Both levels of compaction decreased Ca concentration markedly, often significantly (either * or **) at S5 irrespective of the aggregate size range or watering regime. In the large aggregate size range (A2) Ca concentration was depressed, under continuous watering, by both C1 (*) and C2 (**) levels of compaction at S4.

Magnesium (Appendix, Table 10)

Mean of samplings (Fig. 29,a) Mg concentration in dry matter was significantly (***) reduced by both the C1 and the C2 levels of compaction (main effect). It was also significantly less (***) in the large aggregate-size range (A2) as compared (main effect) with the narrow aggregate-size range (A1). There was a significant interaction (*) between compaction and the aggregate-size range. This interaction was apparent from the non-significant difference in Mg concentration between the two aggregate size ranges in the non-compacted soil (C0), compared with large differences (**) between A1 and A2 at either level of compaction.

There was no significant main effect, or interaction with compaction of the watering regime.

At individual samplings (Fig. 29,b) At all samplings, irrespective of watering regime, the C2 level of compaction depressed Mg concentration in dry matter, often highly significantly, in both aggregate size ranges, but to a greater extent in the large aggregate size range (A2).

Effects of the C1 level of compaction were in general similar to those of C2 but less marked except at S4 and S5 where in the small aggregate size range (A1) Mg concentrations were slightly increased when watering was withdrawn (W0).

The Yield

Fresh matter yield (Appendix, Table 12)

Under watering withdrawal regime (W0). The fresh matter yield (Fig. 30) was increased markedly, but not significantly, by both levels of compaction at S2, but to a greater extent by C1 than by C2 level of compaction (Fig. 30,a). Later, at S2 to S5, the larger plants produced in the compacted soils, especially in the C1 level of compaction, wilted more quickly than the smaller plants in the non-compacted soil (C0) giving rise to a proportionally greater loss in the fresh matter weight.

These effects occured in both aggregate-size ranges but were more marked in the large aggregate-size range (A2).

When the means of all samplings were considered (Fig. 30,b, 1 and 2) both C1 and C2 levels of compaction gave greater yields than the non-compacted soil (C0) with being more marked for C1 than for C2.

Under continuous watering regime (W1)(Fig. 31) The C1 level of compaction gave higher yields than the non-compacted soil (C0) in both aggregate size ranges at all samplings except at S4 where in the narrow aggregate-size range (A1) a slightly lower yield was produced. In the large aggregate-size range (A2), these differences increased with time and were significant at S3 (**), S4 (***) and S5 (***). In the small aggregate-size range (A1), the only significant difference (**) was recorded at S3.

Yields at the C2 level of compaction were not significantly different from those in the non-compacted soil (C0) at any sampling. However, at S4 and S5, the C2 level of compaction gave slightly higher yields than C0 in the large aggregate-size range (A2) but slightly lower than C0 in the narrow aggregate-size range (A1).

When the means of all samplings were considered (Fig. 31,b 1 and 2), the increases in the yield by the C1 level of compaction were pronounced in both aggregate size ranges, being more significant in the large aggregate-size range (A2), from 8.5 to 12.7 g/pot (***) than in the narrow aggregate-size range (A1), from 12.3 to 14.2 g/pot (*). The C2 level of compaction, slightly reduced the yield in the narrow aggregate-size range (A1) and only slightly increased it in the large aggregate-size range (A2).

Interaction. A significant interaction (***) occured between compaction and watering regime (Figs. 30,b 2 and 31,b 2). This interaction took the form of a large increase (***) by C1 and a small decrease (ns) by C2 in the fresh matter yield when watering was continuous (W1) compared with only a small increase (ns) by C1 and a slight increase (ns) by C2 in the fresh matter yield when watering was withdrawn (WO).

The aggregate-size range (Figs. 30, b 3 and 31, b 3) In general, yields for the narrow aggregate-size range (A1) were higher than those for the large aggregate-size range (A2) irrespective of watering regime and compaction level (*** for the mean values).

Dry matter yield (Appendix, Table 13)

Under watering withdrawal regime (WO) (Fig. 32) As would be expected, because of wilting starting at S2 and S3, the pattern of dry matter yield is not similar to that of fresh matter yield.

It is interesting that dry matter yield apparently tended to increase slightly after the onset of wilting irrespective of compaction level in the narrow aggregate-size range (A1) and in CO and C1 in the large aggregate-size range (A2). However, these increases were not significant.

There were no significant effects of either level of compaction on yield of dry matter, but the C1 level of compaction consistently gave greater yields than the non-compacted soil (CO) irrespective of the aggregate-size range. The C2 level of compaction also gave generally higher yields than the non-compacted soil (CO) especially in the large aggregate-size range (A2).

Under continuous watering (W1) (Fig. 33) As comparison of Figs. 31 and 33 shows clearly, the pattern of results of dry matter yield was very similar to that of fresh matter yield. The main difference between these results was in the C2 level of compaction which, comparing with CO and C1 gave proportionally higher dry matter than fresh matter yield. However, effects reading not significant for fresh matter
often
yield were/significant for dry matter yield because of higher standard errors in the fresh matter yield data.

The similarity in the results of fresh matter and dry matter yield of CO and C1 and the slight difference of C2 are supported by evidence from Fig 35,b, where effects of C1 level of compaction on percent dry matter are small and not significant but slightly higher in the C2 level of compaction.

Percent dry matter (Appendix, Table 14)

Under watering withdrawal regime (WO) (Fig. 34,a) At early samplings, S1 to S3, there were little differences in the percent of dry matter between the three compaction levels but at S4 and S5, C1 level of compaction gave higher (ns) values than both CO and C2.

Under continuous watering (W1) (Fig. 35,b) There were no significant differences in percent of dry matter although the C2 level of compaction consistently gave higher values than both CO and C1.

EXPERIMENT II

Soil Water relationships

Soil moisture characteristic curve (Appendix, Table 15) (Fig. 35)

Compaction did not result in marked changes in the soil moisture characteristic curve. In general it tended to increase slightly the moisture retained by the soil at very high tensions, > pF 3 and to decrease it at low tensions < pF3.

Pore size distribution (Fig. 36) In open packing (PO) pore size distribution was calculated from the soil moisture characteristic curves and the total porosity of soil in the pots.

In close packing (PC) and packing with sand (PS) pore size distributions were also determined from the soil moisture characteristic curves and the total porosity of the soil in the pots, assuming that the reductions in total porosities (by close packing in PC and by filling the large pores with sand PS) were in the large pores only, which at saturation, hold the excess water only. This assumption, however, would be safe only if the extra"micro pores" established at points of contact are considered as negligible.

As Fig. 36 shows, compaction resulted in only slight alterations in pore-size distribution. This alteration, in the three packings, is a slight decrease in the percentage of the pores in the range 0.2 - 300 μm (about 4% of total porosity) which has been added, almost equally, to both the pores larger than 300 μm and those smaller than 0.2 μm.

The effect of packing, in both the compacted and non-compacted soils, is more marked than that of compaction but only in reducing the percentage of the macropores (> 300 μm). Close packing reduced the macropores from 22.5% to 15.4% in the non-compacted soil, and from 23.9% to 14.5% in the compacted soil. Packing with sand increased the potential macropores of the soil from 22.5% to 28.3% in the non-compacted soil, but filling these pores with sand actually resulted in reducing the percentage of macropores to 14.5% by packing with sand. In the compacted soil, the increase in the potential macropores of the soil is from 23.9% to 29.1%, but actually the macropores were reduced to 14.6%.

Available water capacity. As compaction showed a slight reduction in the percentage of water held between pF 1.0 and pF 4.2 (Fig. 35), and assuming the effects of the extra "micro-pores" established at points of contact of the aggregates in both close packing (PC) and packing with sand (PS) to be negligible, only a slight decrease by compaction, and no effect of packing, was expected in the AWC of the soil in the pots. Table 8 shows the moisture contents of the soils (the 6 combinations of 2 compaction x 3 packing levels) at S1, where the tension on soil water was that of the mean height of soil columns in the pots, and S3, where wilting (according to Figs. 45 and 46) was considered to have reached the permanent stage. The data of Table 8 show, on average, 14% decrease in AWC by compaction regardless of packing, and also support the assumption that the extra micro-pores at points of contact of the aggregates in PC and PS are not contributing to the AWC.

Table 8 Moisture contents of the soils (% dry weight) at S1 and S3 (Means of 6 determinations).

	PO		PC		PS	
	CO	C1	CO	C1	CO	C1
S1	27.9	25.5	26.9	24.4	25.3	23.0
S3	9.1	9.1	9.0	9.1	9.0	9.3
AWC	18.8	16.4	17.9	15.3	16.3	13.7*
Reduction in AWC by compaction	13%		14%		16%	

* The considerable reduction in the moisture content in PS at S1, as compared with that of PC and PO resulted from the determination being made on weight basis which includes the sand.

Aeration

The effects of compaction and packing on the air capacity of the soil are presented in Fig. 37.

The data show that compaction had very little effects on the air capacity of the soil, but both close packing (PC) and packing with sand showed marked effects in reducing the air capacity of the soil. However, only at pF 1 might such effects of packing be expected to affect the growth of plants where the air capacity is less than a value of 10% often quoted as the level below which plant growth is adversely affected.

Nutrient concentration

As the pots of samplings 3 and 5 of the continuous watering regime

(W1) of this experiment were used for a "change in the design" (see Methods and Materials), the obtained data on nutrient concentrations, as well as on the yield, were not complete for a statistical analysis which would have included all the treatments simultaneously. The statistical analysis was, therefore, carried out on two groups of data separately. The group I analysis included all the 6 samplings but was confined to the watering withdrawal (WO) regime data. The group II analysis included both watering regimes but was confined to samplings 1, 2, 4 and 6. The results presented here are usually of analysis II unless otherwise stated. No statistical analysis was made on the data of the "change in the design".

In Table 9 the effects (mean of all samplings only) of both compaction and packing on the concentration of nutrient elements N, P, K, Na, Ca and Mg in dry matter are summarized according to both statistical analyses. The effect of packing is presented regarding the open packing (PO) as control with which the effects of both close packing (PC) and packing with sand (PS) are compared.

Nitrogen (Appendix, Tables 17,a and b)

Mean of all samplings (Fig. 38,a) Compaction only in packing with sand (PS) and then only when watering was withdrawn (WO) showed a significant reduction (*) in N concentration in dry matter. There was no significant effect, or interaction with compaction, of packing.

At individual samplings (Fig. 38,b) When watering was continuous (W1), compaction in general increased N concentration at S1 and depressed it at S2. The only significant increase, i.e. at S1, was in open packing (*), but the decreases were significant (**) in both open packing (PO) and close packing (PC) at S2 and in packing with sand (PS) at S6 (*).

Table 9. Effects of compaction and packing on nutrient concentration in dry matter.

(1) Analysis I

Treatment	N	P	K	Na	Ca	Mg
C mean of P	-*	ns	+*	ns	ns	ns
C in PO	ns	-*	+**	ns	ns	ns
C in PC	ns	ns	+**	ns	+*	ns
C in PS	-*	-*	-*	ns	-*	-**
PC mean of C	ns	-***	ns	ns	ns	ns
PC in CO	ns	-***	ns	ns	ns	ns
PC in Cl	ns	-*	ns	ns	ns	ns
PS mean of C	ns	-***	ns	ns	ns	ns
PS in CO	ns	-***	ns	ns	ns	+**
PS in Cl	ns	-***	***	ns	ns	ns

(2) Analysis II

		N	P	K	Na	Ca	Mg
C mean of P	(WO	ns	ns	ns	ns	ns	ns
	(Wl	ns	ns	ns	ns	*	ns
C in PO	(WO	ns	ns	ns	ns	ns	ns
	(Wl	ns	ns	ns	ns	ns	ns
C in PC	(WO	ns	ns	+***	ns	+*	ns
	(Wl	ns	ns	ns	ns	+*	+**
C in PS	(WO	-*	ns	ns	ns	-*	-***
	(Wl	ns	ns	-*	ns	ns	ns
PC mean of C	(WO	ns	-*	ns	ns	ns	ns
	(Wl	ns	-*	ns	ns	+*	ns
PC in CO	(WO	ns	-**	-*	ns	-*	-*
	(Wl	ns	ns	ns	ns	+*	ns
PC in Cl	(WO	ns	ns	ns	ns	ns	-*
	(Wl	ns	ns	ns	ns	ns	ns
PS mean of C	(WO	ns	-***	-**	ns	ns	ns
	(Wl	ns	-**	ns	ns	ns	+*
PS in CO	(WO	ns	-***	ns	ns	ns	+**
	(Wl	ns	ns	ns	ns	ns	+*
PS in Cl	(WO	ns	-***	-**	ns	ns	-*
	(Wl	ns	-**	-**	ns	ns	ns

The effects of packing on N concentrations were not marked. However, close packing (PC) depressed the concentration (**) at S1 irrespective of compaction, and packing with sand (PS) increased it (*) in the compacted soil at S6.

When watering was withdrawn (WO) compaction depressed N concentration significantly in dry matter at S2 in both close packing (*) and packing with sand (**). Packing showed opposite effects of close packing and packing with sand at S2, PC depressed the concentration (*) in the compacted soil but PS increased it (**) in the non-compacted soil.

Interactions. The following significant interactions were recorded:

1. Compaction and sampling (***) which took the form of an increase in N concentration by compaction at S1 (*), a decrease at S2 (***) and no significant effects at S4 and S6.

2. Packing and sampling (*) which took the form of significant decreases by close packing (***) and packing with sand (*) at S1, non-significant decreases by both packings at S2 and S4 but slight increases by both packings at S6.

3. Sampling, compaction and watering (*) which took the form of decreases (ns) in N concentration in dry matter at S1, S2 and S6, and an increase (ns) at S4 when watering was withdrawn (WO), compared with increases at S1 (**), S4 (ns) and S6 (ns) but a decrease (***) at S2 when watering was continuous.

4. Sampling, packing and watering (*) which took the form of a complex pattern of mostly non-significant individual effects of S, P and W.

Phosphorus (Appendix, Tables 18,a and b)

Mean of all samplings (Fig. 39,a) Compaction showed no significant effects on P concentration in dry matter over the means of packings and watering regimes. However, under watering withdrawal regime (WO) compaction depressed the concentration slightly in both open packing (PO) and packing with sand (PS). The significance of these effects were shown in analysis I at (*).

Both close packing (PC) and packing with sand (PS) reduced P concentration significantly in dry matter. The reduction by close packing (from 0.32% to 0.31% (*) main effect) occured mainly in the non-compacted soil when watering was withdrawn (**). In analysis I, the main effect of close packing was highly significant (***) and occured in both the non-compacted (***) and the compacted (*) soils. Packing with sand (PS) showed a more marked main effect, from 0.32% to 0.30% (***) and occured in the non-compacted soil irrespective of watering regime (***, in WO and ** in W1) and in the compacted soil when watering was withdrawn (***). However, there were no significant interactions between packing and compaction or between packing and watering.

At individual samplings (Fig. 39,b) When watering was continuous (W1) compaction showed no marked effects on P concentration in dry matter except an increase (*) at S2 in close packing and a reduction (*) at S4 in packing with sand. Packing also showed no marked effects except reductions by packing with sand (PS) at S1 in both the compacted (**) and the non-compacted (***) soils.

When watering was withdrawn (WO) compaction depressed P concentration slightly but consistently in packing with sand (PS), at all samplings in open packing and close packing except at S2 in (PO) and at S6 in

(PC) but there was a significant (*) increase at S2 in close packing.

Packing, in general reduced P concentration in both close packing and packing with sand. Reductions by PS were marked in most of the samplings (* or **) irrespective of compaction, but by close packing the only significant reduction (*) was at S2 in the non-compacted soil.

Interactions. The following significant interactions were recorded:

1. Sampling and compaction (**) which took the form of a decrease (*) in P concentration by compaction at S1, no effect at S2, a decrease (*) at S4 and no effect at S6.

2. Sampling and packing (*) which took the form of decreases by both close packing (**) and packing with sand (***) at S1, and (*) and (**) respectively at S2, but no effects of close packing at S4 and S6 compared with decreases (*) at these two samplings (S4 and S6) by packing with sand.

Potassium (Appendix, Tables 19,a and b)

Mean of all samplings (Fig. 40,a) Compaction, in general, increased K concentration in dry matter in both open packing (PO) and close packing (PC) and reduced it in packing with sand (PS), irrespective of watering regime. The only significant effects, however, were in close packing when watering was withdrawn, from 3.94% to 4.18% (***) and in packing with sand when watering was continuous, from 3.60% to 3.45% (*). Analysis I showed similar effects of compaction in close packing but at (**) and showed that the increase by compaction in open packing was significant (**) and the reduction in packing with sand was also significant (*). These effects resulted in a significant interaction (***) between compaction and packing.

Packing with sand depressed K concentration in dry matter significantly (**) in the compacted soil, irrespective of watering regime. Close packing also depressed the concentration but less markedly (*) and only in the non-compacted soil when watering was withdrawn (WO).

At individual samplings (Fig. 40,b) When watering was continuous (W1) compaction, in close packing (PO) increased K concentration in dry matter significantly (***) at S2, but reduced it, in packing with sand (**) at S2 and S4. Close packing depressed K concentration at S2 in the non-compacted soil (***) but increased it at S4 in both the compacted (***) and the non-compacted (*) soils and at S6 in the non-compacted soil (*). Packing with sand (PS) reduced K concentration (***) at S2 in the compacted soil but increased it (**) at S4 in the non-compacted soil.

When watering was withdrawn (WO) compaction increased K concentration, in close packing (PC) at S1 (**) and S2 (***) but reduced it in packing with sand (PS) at S4 (*).

Packing resulted in reductions in K concentration in dry matter by close packing (PC) in the non-compacted soil at S2 (**) and by packing with sand (PS) in the compacted soil at S1 (***).

These differences in packing effects with both watering regime and compaction at different samplings resulted in significant interactions between packing and sampling (*** in analysis I), packing, sampling and compaction (*** in analysis I) and packing, sampling and watering (* in analysis II).

Sodium (Appendix, Tables 20,a and b, and Figs. 41, a and b)

Despite the quite large differences shown in Fig. 41 (a and b), there were no significant effects (with the exception of a reduction (*) by compaction in packing with sand, under continuous watering at S4) or interactions of compaction and packing on Na concentration in dry matter. However, the standard errors were very high.

Calcium (Appendix, Tables 21, a and b)

Mean of all samplings (Fig. 42,a) Compaction increased Ca concentration in dry matter in close packing (PC) irrespective of watering regime (*), but depressed it in packing with sand when watering was withdrawn (*). These effects gave rise to a significant interaction (**) between compaction and packing (both analyses).

Packing, when the mean of the two compactions was taken increased Ca concentration (*) by close packing when watering was continuous (W1). When the two compaction levels were considered separately, close packing (PC) in the non-compacted soil depressed concentration (*) when watering was withdrawn (WO) but increased it (*) in the compacted soil when watering was continuous (W1).

At individual samplings (Fig. 42,b) When watering was continuous (W1), compaction tended to increase Ca concentration in dry matter at later samplings. Increases were significant (**) at S4 and S6 in close packing (PC) and at S6 in packing with sand (PS). Packing tended to increase Ca concentration in dry matter in the compacted soil where significant increases by close packing occurred at S4 (*) and S6 (***) and by packing with sand at S6 (**).

When watering was withdrawn (WO) compaction again tended to increase Ca concentration at later samplings. Ca concentration was depressed at

S1 (*) in both open packing (PO) and packing with sand (PS) and at S2 (**) in packing with sand, but was increased in close packing (PC) at S1 (ns) and S4 (*). Packing, in the compacted soil, showed an increase in Ca concentration, by close packing at S1 (**), but in the non-compacted soil depressed the concentration by close packing at S4 (**) and in packing with sand at S2 (**).

Interactions. In addition to the significant interaction shown earlier between compaction and packing, the following significant interactions were also recorded:

1. Sampling and compaction (***) which took the form of decreases by compaction in Ca concentration in dry matter at S1 (ns) and S2 (*) but increases at S4 (ns) and S6 (***).
2. Sampling and packing (**) which took the form of an increase (ns) by close packing but a decrease by packing with sand (ns) at S1, decreases by PC (ns) but increases (ns) by PS at S2 and S4, and increases by both PC (*) and PS (*) at S6.

Magnesium (Appendix, Tables 22,a and b)

Mean of all samplings (Fig. 43,a) Compaction, in general, increased Mg concentration in dry matter in both open packing (PO) and close packing (PC) irrespective of watering regime but depressed it in packing with sand (PS) when watering was withdrawn (WO). Although the significant effects were only the increase in close packing (**) under continuous watering (W1) and the decrease in packing with sand (***) when watering was withdrawn (WO), both analyses showed a significant interaction between compaction and packing (**).

Close packing (PC) depressed Mg concentration in dry matter (*) irrespective of compaction but only when watering was withdrawn (WO). Packing with sand (PS) increased Mg concentration (* or **) in the non-compacted soil irrespective of watering regime but depressed it (*) in the compacted soil when watering was withdrawn (WO).

At individual samplings (Fig. 43,b) Under continuous watering (W1), compaction consistently increased Mg concentration in close packing (PC), the effect being significant (*) at S4. Compaction also increased the concentration significantly (**) in open packing (PO) at S1. There were no significant effects of compaction in packing with sand (PS). Close packing significantly increased Mg concentration at S6 (***) in the compacted soil, but packing with sand (PS) showed significant increases (*) at S4, in the non-compacted soil, and at S6 in the compacted soil.

When watering was withdrawn (WO) compaction showed marked decreases in packing with sand (PS) at S2 (***) and S6 (**) and otherwise showed slight increases in both open packing and close packing at all samplings (with the exception of the S6 in PO). Packing with sand (PS) depressed the concentration (**) in the compacted soil but increased it (**) in the non-compacted soil both at S2.

Interactions. In addition to the significant interaction shown earlier between compaction and packing, the following significant interactions were recorded:

1. Sampling and compaction (*) which took the forms of increases, by compaction, in Mg concentration in dry matter at S1 (*) and S4 (ns) but decreases at S2 (ns) and S6 (ns).
2. Sampling packing watering (*), with continuous watering (W1), close packing resulted in decreases at S1 (*) and S2 (ns), no effect at S3 and a significant increase (***) at S4, but packing with sand resulted in no effect at S1, a decrease at S2 (ns) and increases (*) at S4 and S6. When watering was withdrawn (WO), close packing

showed no effect at S1 and decreases at S2 (ns), S3 (*) and S4 (*), but packing with sand resulted in an increase at S1 (ns), a decrease at S2 (ns), an increase at S3 (ns) and no effect at S4.

The Yield

Fresh matter yield. (Appendix, Tables 23,a and b)

Under continuous watering (W1) (Figs. 44 and 47,a). The fresh matter yield, in general showed slight response to compaction at later samplings in both close packing (PC) and packing with sand (PS). In close packing the only significant response was at S6, from 59.5 g/pot to 69.2 g/pot (*) and in packing with sand at S4, from 29.5 g/pot to 39.0 g/pot (*). In open packing (PO), in contrast to the other two levels of packing, the yield was depressed by compaction at S6, from 56.5 g/pot to 44.3 g/pot (*). However, when the means of the three packings were considered compaction increased the yield from 30.0 g/pot to 36.6 g/pot (*) at S4 and slightly at S6, otherwise it depressed the yield slightly.

When the means of the samplings were considered (Fig. 47,a) compaction showed no significant effects whether the three packings were considered separately (Fig. 47, a1) or when their mean was considered (Fig. 47,a2).

Packing (Fig. 44), in general, showed increases in the yield by both close packing (PC) and packing with sand (PS) at later samplings but in the compacted soil only, significant increases being only at S6, from 44.3 g/pot to 69.2 g/pot (**) by close packing and to 6.45 g/pot (*) by packing with sand.

When the means of all samplings were taken (Fig. 47, a1) both close packing (PC) and packing with sand (PS) showed significant increases in the yield (**) in the compacted soil, but not in the non-compacted soil. When the mean of the two compaction levels was considered (Fig. 47, a3), the increase in the fresh matter yield only in close packing was significant (*). However, the interaction between compaction, and packing, when the mean of both watering regimes was taken, was not significant.

Under watering withdrawal (WO) (Fig. 45 for analysis I and Figs. 46 and 47,b for analysis II). As comparison of Figs.45 and 46 clearly shows that the results of both analyses are very similar, the results of analysis II only will be dealt with.

Neither compaction nor packing (whether individual samplings or when the means of all samplings were considered) showed any significant effects on the fresh matter yield. However, from S2 and onwards, i.e. from onset of wilting, the loss in fresh matter weight was greater in the compacted soil, than in the non-compacted soil irrespective of packing.

The effect of packing, on the fresh matter yield, was slightly different from that under continuous watering, in that close packing (PC) gave the lowest yield while at W1 gave the highest.

Dry matter yield (Appendix, Tables 24,a and b)

Under continuous watering (Figs. 48,a and 49,a) As comparisons of Figs. 48, a with 44 and Figs. 49, a with 47, a show clearly, the patterns of results in dry matter yield and those of fresh matter yield were very similar except that in the non-compacted soil, the dry matter yield tended to be proportionally higher than the fresh matter yield. This effect was more apparent in packing with sand (PS) where the significant response of F.M. at S4 to compaction was not significant in D.M. and the higher yield of F.M. at S6 was in the compacted soil but of D.M. was in the non-compacted soil. The effect was also apparent but less markedly, in close packing (PC) but not in open packing. This effect was clearly reflected in the percent dry matter data (Fig. 50, a).

However, the main difference in the statistical analysis between the results of F.M. and D.M. was that effects reading not significant in fresh matter were often significant in dry matter. This was because of the relatively high standard errors in F.M. data than in D.M. data.

Under watering withdrawal (Figs. 48, b and 49, b) As would be expected, because wilting started at S2 and S3, the pattern of dry matter yield was not similar to that of the fresh matter yield. However, compaction, in agreement with the fresh matter (see Fig. 50,b of percent dry matter) yield depressed the dry matter yield (but not significantly) at S2 and onwards in open packing (PO), from S4 and onwards in close packing (PC) and at S4 and S6 in packing with sand (PS).

Percent dry matter (Appendix, Tables 25, a and b)

As would be expected from a comparison of fresh matter and dry matter data, percent dry matter data showed, that, under continuous watering (Fig. 50, a), compaction tended to have depressing effects (ns) in both close packing (PC) and packing with sand (PS) at later samplings but not in open packing (PO). Packing showed a decrease (ns) in percent dry matter in the compacted soil in both close packing (PC) and packing with sand (PS) but otherwise showed no special effects.

When watering was withdrawn (WO) compaction did not show marked effects on percent dry matter (Fig. 50, b) at early samplings but at S6 showed a significant increase (*) in packing with sand and a slight decrease in close packing. Packing, in general, showed no effects except a decrease (*) in percent dry matter at S6 in the non-compacted soil.

There were no significant interaction between compaction and packing over the mean of the two watering regimes.

Results of the "change in the design".

The data of the "change in the design" (see Materials and Methods) are tabulated in Table 10. However, no statistical analysis was carried out on the data.

Table 10. Fresh and dry matter yields (g/pot) when two levels of stress were applied.

Soil treatment	Fresh matter		Dry matter	
	50% wilting	10% wilting	50% wilting	10% wilting
CO PO	60.0	68.1	10.3	11.8
CO PC	59.4	64.3	9.7	10.6
CO PS	52.7	71.0	8.5	11.8
Cl PO	55.8	65.3	9.3	11.2
Cl PC	55.9	58.8	9.4	10.1
Cl PS	56.7	60.2	9.3	10.3

Fresh matter. The data on fresh matter, showed a reduction by compaction under the high stress (50% wilting) from 57.4 g/pot to 56.1 g/pot (over the mean of the three packings). This reduction occurred mainly in open packing (PO) and close packing (PC) while in packing with sand the fresh matter yield was actually higher in the compacted soil than in the non-compacted soil, 56.7 g/pot as compared with 52.7 g/pot. Under the low stress (10% wilting) compaction (over the mean of the three packings) again reduced the fresh matter yield, from 67.8 g/pot to 61.4 g/pot but the reduction was almost equally marked in the three packings.

Under both stresses, open packing (PO) resulted in the highest yield (over the mean of the two compaction levels) which was 57.9 g/pot under the high tension and 66.7 g/pot under the low tension. Under the high tension, close packing (PC) resulted in a higher fresh matter yield than packing with sand (PS), 57.6 g/pot as compared with 54.7 g/pot, but under the low tension packing with sand (PS) produced 65.6 g/pot which was higher than the 61.5 g/pot produced in the close packing (PC).

Dry matter. Dry matter yield showed almost the same effects of compaction and packing as did the fresh matter yield.

In summary, as the results of the "change in the design" were in general, showing higher differences in the yield than those of the experiment itself, it was concluded that the cumulation of the effects of compaction and/or packing, on the availability of soil water to plants through imposing more than one period of stress, results in an easier detection of small differences.

EXPERIMENT III

Soil water relationships

Soil moisture characteristic curves (Appendix, Table 26 and Figs. 51 and 52). The effect of compaction on the retainability of water by soil was marked in both aggregate-size ranges. At all pF values up to 2.7 the effect was highly significant (***) in both aggregate-size ranges. At high pF values compaction resulted in a slight decrease in the retainability of water in the small aggregate size range.

Pore-size distribution (Fig. 53) Although compaction resulted in slight decreases in the total porosity in both aggregate-size ranges, within the total porosities there were marked decreases (percentage of total porosity) in both the pores > 300 μm in diameter, which are drained of their water at pF 1.0, and those < 0.2 μm, which retain unavailable water at pF 4.2, with the resultant marked increases in the percentage of the pores in the range 0.2 μm to 300 μm.

In the small aggregate-size range, 0.5-4.8 mm, (A1), the decrease in total porosity was from 65.5% to 65.1%. Decreases (%total porosity) in pores > 300 μm and those <0.2 μm in diameter were from 55.6% to 48.4% and from 15.0% to 14.8% respectively, giving rise to an increase from 29.4% to 36.8% in the pores in the range 0.2 -300 μm in diameter. In the large aggregate-size range, 4.8-9.5 mm, (A2), the decrease in the total porosity was from 65.9% to 65.5%. Decreases (% total porosity) in the pores > 300 μm and those < 0.2 μm in diameter were from 56.4% to 51.9% and from 17.6% to 15.0% respectively, giving rise to an increase from 26.0% to 33.1% in the pores in the range 0.2 -300 μm in diameter.

Available water capacity As would be expected, the increase in the percentage of the pores in the range 0.2 -300 μm in diameter, which hold the available water, resulted in marked increases (Table11) in the

AWC of the soil in both aggregate-size ranges, despite the slight decreases in the total porosity. Increases were 23% in the small aggregate-size range (A1) and 12% in the large aggregate-size range (A2)

Table 11. The available water capacity calculated from the soil moisture characteristic curves as the difference in % moisture content at pF 1.0 and 4.2.

Soil		% moisture content at pF 1.0	at pF 4.2	AWC g/100g	available water as % AWC of CO
A1	CO	34.0	11.3	22.7	100
	C1	38.6	10.6	28.0	123
A2	CO	33.7	11.3	22.4	100
	C1	36.6	11.4	25.2	112

Available water at specific tensions (Fig. 54) Compaction has resulted in considerable increases in the available water at all the tensions within the available water range, particularly at low tensions where the water is more easily available for the use by plants. The data of Fig. 54 express the available water at specific tensions as percentage of the AWC of the non-compacted soil.

Aeration

The effect of compaction on the air capacity of the two aggregate-size ranges in the pots are presented in Fig. 55. The data show that compaction had actually reduced the air capacity in both aggregate-size ranges and that the effect is higher at lower tensions. However, even at pF 1 when the air capacity is at the minimum level, the level is well above the 10% level often quoted as the level below which plant growth is adversely affected.

Nutrient concentration

In the statistical analyses of both the nutrient concentration in dry matter and the yield data, only one degree of freedom was available for the main effect of tension. Neither analysis was, therefore, used in evaluating the significance of tension effects. However, tension showed marked effects on the yield, as will be shown later, but was not expected to show any considerable effect on the nutrient concentration in dry matter, as excess water (drainage) was kept at minimum. Table 10 is a summary of the significance of the effect of compaction, under all other treatments including tension, on the concentration of the nutrient elements N, P, K, Na, Ca and Mg in plant dry matter.

Nitrogen (Appendix, Table 28)

Mean of all samplings (Fig. 56,a) Neither compaction nor aggregate-size range showed significant effects on N concentration in dry matter irrespective of tension.

At individual samplings (Fig. 56,b) In general the effects of compaction appeared to be more marked in the small aggregate-size range (A1) than in the large aggregate-size range (A2) under both tensions. In the small aggregate-size range (A1) compaction tended to depress N concentration at S1 to S3 irrespective of tension, but increased it slightly at S4 and S5 under 100 cm tension and at S4 (*) under 50 cm tension. In the large aggregate-size range effects were negligible except at S4 when compaction reduced the concentration under 100 cm tension (*).

N concentration in dry matter was generally slightly higher in the large aggregates (A2) than in the small aggregates (A1). This effect of the aggregate size was significant at S4 in the non-compacted soil under both 100 cm (*) and 50 cm (**) tension and at S2 in the compacted soil (*) under 100 cm tension. However, in the compacted soil

Table 10. The significant effects of compaction on nutrient concentrations in plant dry matter.

			S1	S2	S3	S4	S5
N	T100	A1	ns	-*	ns	ns	ns
		A2	ns	ns	ns	-*	ns
	T50	A1	-*	ns	ns	+*	ns
		A2	ns	ns	ns	ns	ns
P	T100	A1	-*	-*	ns	-*	ns
		A2	ns	ns	ns	ns	ns
	T50	A1	ns	ns	ns	+*	ns
		A2	ns	ns	ns	ns	ns
K	T100	A1	ns	ns	ns	-***	ns
		A2	ns	ns	ns	ns	ns
	T50	A1	ns	ns	-*	ns	ns
		A2	ns	ns	ns	-*	ns
Na	T100	A1	ns	+*	-*	ns	ns
		A2	ns	ns	ns	ns	ns
	T50	A1	ns	ns	ns	ns	ns
		A2	ns	-*		ns	ns
Ca	T100	A1	-**	ns	ns	ns	ns
		A2	ns	ns	ns	ns	ns
	T50	A1	ns	ns	ns	ns	ns
		A2	ns	ns	ns	ns	ns
Mg	T100	A1	-*	ns	ns	ns	ns
		A2	ns	ns	ns	ns	ns
	T50	A1	ns	ns	-*	+**	ns
		A2	ns	ns	ns	ns	ns

the concentration was higher (*) in the small aggregates(A1) than in the large aggregates (A2) at S5 under 100 cm tension.

Interaction A significant interaction (**) was recorded between sampling, compaction and the aggregate size range. In the small aggregates (A1) compaction tended to depress N concentration in dry matter at early samplings, and to increase it at later ones, but in the large aggregates compaction had not effect on the concentration at S1, while it depressed it at S2, S4 and S5.

Phosphorus (Appendix, Table 29)

Mean of all samplings (Fig. 57,a) Compaction only in the small aggregate size range (A1) and then only under 100 cm tension showed a significant effect on P concentration in dry matter, where it was reduced from 0.19% to 0.18% (*). The aggregate size range, however, showed more marked effects than compaction where P concentration was significantly lower in the large aggregates (A2) than in the small aggregates (A1) in the non-compacted soil irrespective of tension and in the compacted soil under 50 cm tension.

At individual samplings (Fig. 57,b) Compaction showed marked effects on P concentration in dry matter in the small aggregate size range, where the concentration was reduced at S1, S2 and S4 significantly (*) under 100 cm tension, but was increased (*) at S4 under 50 cm tension. In the large aggregates, although there were no significant effects of compaction, compaction tended to increase the concentration. This tendency was apparent at all samplings, except at S2 under 50 cm tension.

The effect of the aggregate size range on P concentration in dry matter was marked. In the large aggregates (A2) the concentration tended to be/frequently significant less (*), than that in the small aggregates

(A1) at S1, S3, S5 under 50 cm tension; at S2 and S4 under 100 cm tension in the non-compacted soil; at S2 under 50 cm tension and at S5 under 100 cm tension in the compacted soil.

Interactions A significant interaction (*) was recorded between compaction and aggregate size range which took the form of a decrease in the concentration by compaction in the small aggregates (A1), but an increase in the large aggregates (A2).

Potassium (Appendix, Table 30)

Mean of all samplings (Fig. 58,a) K concentration in dry matter was markedly reduced by compaction irrespective of tension and the aggregate size, but the reduction was more marked in the small aggregate size range (A1) than in the large aggregate size range (A2) and then/under 100 cm tension (***) than under 50 cm tension (*). The aggregate size range showed no marked effects on K concentration in dry matter, but it was slightly higher in small aggregates (A1) than in the large aggregates (A2) in the non-compacted soil, and slightly higher in the large aggregates (A2) than in the small aggregates (A1) in the compacted soil. This interaction of compaction and aggregate size range was significant at 10% level.

At individual samplings (Fig. 58,b) Compaction showed marked reductions in K concentration in dry matter in the small aggregates (A1) at all samplings irrespective of tension, except at S2 under 50 cm tension where a slight increase was recorded. Reductions were significant at S3 under 50 cm tension (*) and at S4 under 100 cm tension (***). In the large aggregate (A2) compaction showed slight increases at S2 under 100 cm tension and at S3 under 50 cm tension, otherwise showed either reductions or no effects. Under 50 cm tension a significant reduction (*) was recorded at

S4. The effect of the aggregate size range was less marked than that of compaction. In general K concentration was depressed in the large aggregates (A2) in the non-compacted soil, but in the small aggregates (A1) in the compacted soil. The only significant effect was at S4 in the compacted soil under 100 cm tension where in the large aggregates (A2) the concentration was higher (*) than in the small aggregates (A1).

Interactions A significant interaction (***) was recorded between sampling, compaction aggregate size range and tension. In the non-compacted soil, K concentration was higher in the large aggregates (A2) than in the small aggregates (A1) at S1 under 100 cm tension, but not at S2-S5, while under 50 cm tension it was not higher at S1, but was higher at S2 and S4. The parallel effects in the compacted soil were all opposite.

Sodium (Appendix, Table 31)

Mean of all samplings (Fig. 59,a) Neither compaction nor the aggregate size range showed significant effects on Na concentration in dry matter.

At individual samplings (Fig. 59,b) As in the previous experiments, standard errors were rather high and no easily understood pattern of effects of compaction and aggregate size range was obtained. However, the only significant effects of compaction were reductions (*) in Na concentration in dry matter at S2, in the large aggregates (A2) under 50 cm tension and at S3 in the small aggregates (A1) under 100 cm tension and an increase at S2 in the small aggregates under 100 cm tension. The aggregate size range showed no significant effects.

Interaction A significant interaction (*) was recorded between sampling and compaction which took the form of increased Na concentration at S1 (ns) and S4 (ns) but depressed concentrations at S2 (ns), S3 (**) and

S5 (ns) resulting from compaction.

Calcium (Appendix, Table 32)

Mean of all samplings (Fig. 60,a) Neither compaction nor the aggregate size showed significant effects on Ca concentration in dry matter.

At individual samplings (Fig. 60,b) Compaction only in the small aggregates (A1) and then under 100 cm tension showed effects on Ca concentration in dry matter where it was reduced consistently but not significantly except at S1 (**). Ca concentration was also reduced (ns) in the large aggregates (A2) from S3 and onward. The effect of the aggregate size range was more marked than that of compaction but mainly in the compacted soil where at S1 Ca concentration in dry matter was higher (**) in the large aggregates (A2) than in the small aggregates (A1) under 100 cm tension, but at S4 was higher in the small aggregates (A1) than in the large aggregates (A2) under 50 cm tension. There were no significant interactions.

Magnesium (Appendix, Table 33)

Mean of all samplings (Fig. 61,a) Compaction significantly (* or **) reduced Mg concentration in dry matter under both tensions in both aggregate size ranges except in the large aggregates under 100 cm tension. The aggregate size range showed no marked effects on Mg concentration in dry matter.

At individual samplings (Fig. 61,b) In both the small aggregates (A1) under 100 cm tension and the large aggregates under 50 cm tension, compaction consistently reduced Mg concentration, but only at S1 in A1, was the reduction significant (*). In the small aggregates (A1) under 50 cm tension and the large aggregates (A2) under 100 cm tension, there were again reducing effects of compaction but a number of increasing effects were also recorded none of which were significant except at S4 in A1 where the increase was significant (**). The differential effects of the aggregate size range on Mg concentration in dry matter at individual samplings was also marked. In the compacted soil, the concentration was consistently higher in the large aggregates (A2) than in the small aggregates (A1) under 100 cm tension, with the difference being significant at S1 (***) and S2 (*). In the non-compacted soil marked effects were recorded under 50 cm tension only, where, at S3, the concentration was lower (*) in the large aggregates (A2) than in the small aggregates (A1). At S4, it was higher (*) in the large aggregates (A2) than in the small aggregates (A1).

Interactions A significant interaction (***) was recorded between tension, compaction and aggregate size range. In the small aggregates (A1) Mg concentration was reduced in dry matter by compaction significantly (**) under 100 cm tension and slightly under 50 cm tension, while in the large aggregates (A2) compaction showed no effect on Mg concentration under 100 cm tension but significantly (*) reduced it under 50 cm tension.

The Yield

Fresh matter yield (Appendix, Table 35) As the last sampling (S5) was carried out while the plants were at the wilting stage (See Methods and Materials), only the data of samplings 1 to 4 were used in the statistical analyses on fresh matter yield and percent dry matter.

At individual samplings (Fig. 62) The fresh matter yield showed consistent responses, often significantly (*-***) to compaction irrespective of aggregate size range or tension. Over the means of the two aggregate size ranges and the two tensions, the response of fresh matter yield to compaction was significant at all samplings and was progressively higher

(Fig. 63) from S1 (*) to S4 (***) except that at S3, the increase was slightly less marked (though still reading ***) than that at S2. The responses of the fresh matter yield to compaction were of similar patterns in the two aggregate size ranges under the same tension, but showed some differences when the tensions were compared with each other irrespective of aggregate-size range, especially at S3, where under 100 cm tension the response was the lowest of any of the samplings but under 50 cm tension was the highest (Fig. 64) giving rise to a significant interaction (**) between tension, compaction and sampling.

The aggregate size range showed no significant effects on the fresh matter yield over the mean of all compaction and tension treatments. However, when the means of the two compaction levels were considered, the fresh matter yield consistently but not significantly responded to the small aggregates (A1) over the large aggregates (A2) under 100 cm tension, but to the large aggregates (A2) over the small aggregates (A1) under 50 cm tension giving rise to a significant interaction (***) between tension and the aggregate size range, and to no main effect of the aggregate-size range.

There were consistently higher yields under 50 cm tension than under 100 cm tension with the effect being, in general, more marked in the large aggregates (A2) than in the small aggregates (A1), and more marked in the non-compacted soil than in the compacted soil. The differences between the yield under the two tensions, over the means of the two compaction levels and the two aggregate-size ranges, were progressively higher in samplings 1 to 4, being significant(*)at S2,(**)at S3 and(***) at S4.

Means of all samplings (Fig. 65) The fresh matter yield responded significantly (***) to compaction irrespective of aggregate-size range and tension (Fig. 65,I). Over the means of the two aggregate-size ranges and the two tensions, the increase in fresh matter yield (Fig. 65,II) was from 35.1 g/pot to 38.7 g/pot (***). When the effect of compaction was considered in the two aggregate-size ranges separately, taking the mean effects of the two tensions, it appeared to be slightly more pronounced in the small aggregates (A1), where the increase was 10.5% of the yield in non-compacted soil, than in the large aggregates (A2) where the increase was 9.1% (Fig. 65, IV). When the effect of compaction was considered under the two tensions separately, taking the mean effect of the two aggregate size ranges, it appeared to be slightly more pronounced under 100 cm tension, where the increase was 10.6% of the yield in the non-compacted soil, than under 50 cm tension where the increase was 10.0% (Fig. 65,V).

The aggregate size range showed no effects on the fresh matter yield at either compaction level when the mean effect of the two tensions was taken (Fig. 65,IV), but the fresh matter yield responded differently to the aggregate-size range under the two tensions when taking the mean effect of the two compaction levels (Fig. 65,VI). Under 100 cm tension the yield was significantly higher (**) in the small aggregates (A1) than in the large aggregates (A2), but under 50 cm tension the yield was higher (**) in the large aggregates (A2) than in the small aggregates (A1), giving rise to the previously shown significant interaction (**) between tension and the aggregate size range.

Tension, as was expected, showed marked effects on the fresh matter yield. Under 50 cm tension the yield was higher (***) than that under 100 cm tension irrespective of compaction or aggregate size range effects. When taking the mean effect of the two aggregate ranges (Fig. 65,V), the significance of the comparative difference in the yield between the two tension levels was slightly more in the non-compacted soil, where the difference was 12.7% of the 100 cm tension yield, than in the compacted soil, where the difference was 12.1%. When taking the mean effect of the two compaction levels (Fig. 65, VI), the significance of the difference in the yield between the two tension levels was markedly more in the large aggregates (A2), where the difference was 17.3% of the 100 cm tension yield than in the small aggregates (A1), where the difference was 7.8%.

Dry matter yield (Appendix, Table 36 and Figs. 66, 67, 68 and 69) As would be expected the dry matter yield results showed the same pattern of effects of compaction, aggregate-size range and tension as the fresh matter yields. In the dry matter yield analysis, the data of all samplings were included, and the effects at the period between S4 and S5 when plants were at the wilting stage, i.e. not complete cycle (see Table 13), represent a continuation of those at S1 to S4.

The effect of the aggregate-size range on the dry matter yield was in fact identical to its effect on the fresh matter yield. The effects of compaction and tension appeared to be more marked, especially of compaction, on the dry matter yield than on the fresh matter yield. This may be seen from the corresponding figures of the two yields and from Table 12, which shows the response of the two yields, expressed as percentage of the "control" to the main effects of compaction, lesion and aggregate-size range. Fresh matter yield response to compaction was 10.3% while that of dry matter yield was 14.6%.

However, as standard errors of dry matter data were relatively slightly higher than those of fresh matter data, effects which were reading significant in fresh matter were often reading non-significant in dry matter yield.

Table 12. Responses of fresh matter and dry matter yields to the effects of compaction, reduced stress and differences in aggregate size range (% of control).

Effect of	Response of	
	F.M. Yield	D.M. Yield
Compaction	+ 10.3%	+ 14.6%
50 cm tension over 100 cm tension	+ 12.3%	+ 12.4%
Large aggregate size range A2 over small aggregate size range A1	+ 0.3%	- 0.7%

Percent dry matter (Appendix, Table 37) As would be expected from the discussion on the dry matter yield, only compaction showed significant effects on percent dry matter. These effects are graphically presented in Fig. 70 at both (a) individual samplings and (b) means of all samplings.

Fresh matter yield and % dry matter at S5 These are tabulated (means only) in Table 13. The general pattern is very similar to those of the S1-S4, except that % dry matter is higher due to the fact that the plants were at wilting stage. It is interesting to notice that the difference in the % dry matter between the data from the non-compacted soil and that from the compacted soil is relatively smaller than those at S1-S4 indicating that the plants in the compacted soil were wilting less than those in the non-compacted soils.

Table 13. Fresh matter yield g/pot at wilting stage (sampling 5) its dry matter content %.

		Fresh matter yield		% Dry matter	
	Tension	A1	A2	A1	A2
non-compacted	100	39.66	36.36	23.37	23.07
	50	42.88	42.90	23.81	23.66
com-pacted	T100	41.82	41.71	24.65	24.52
	T50	45.92	47.45	24.48	24.02

Results of the Supplementary Experiment The data of the supplementary experiment are tabulated (means only) in Table 14.

Table 14. Yield data of the supplementary experiment.

	CO		C1	
	A1	A2	A1	A2
Fresh matter yield	89.74	81.19	90.37	84.66
Dry matter yield	14.35	12.71	15.29	14.00
% Dry matter	15.99	15.65	16.85	16.54

The data indicate that despite that the moisture contents, soils were continuously kept within the available range, compaction resulted in increases in both the fresh matter yield and the dry matter yield, with the effect being more pronounced in the large aggregates (A2) than in the small aggregates (A1) in contrast to that in S1-S4 which in general was more pronounced in A1 than in A2. The dry matter yield, again responded more than the fresh matter yield resulting in higher percentages of dry matter in agreement with the data of S1-S4.

Discussion

It has been pointed out in the review of literature that the soil factors which are related to the growth of plants, i.e. soil water, soil air, soil nutrient status, mechanical impedance and soil thermal properties, are all affected by compaction and that the isolation of any one of these factors from the others, for experimental purposes is difficult. However, the main objective of this work was to study the effect of compaction, through the alterations in pore-size distribution, on soil water relationships and consequently on the availability of soil water to plants. This objective was approached by compacting three soils, crushing them and using compacted and non-compacted aggregates of specific size ranges for,

1. Measuring, by laboratory methods, the effect of compaction on soil water relationships.
2. Evaluating, in pot experiments, the response of established plants (clover) to such effects of compaction on soil water relationships. In the experiments the isolation of this factor, i.e. soil water relationships, from the other factors was attempted.

The three soils, all from the same soil series (Beil), have been described in "Methods and Materials". These soils were chosen because of their suitable textures and highly stable structures. The texture, being a clay loam, and hence plastic enough at the right moisture content to allow the soil to respond to the action of an applied force, was considered suitable to achieve a degree of compaction. The high structural stability was especially important in order to maintain, in the aggregates, the established degree of compaction in both the pot experiments and the laboratory determinations of various physical properties in which aggregates of specific size ranges had to be used. However, the three soils were different in their past history. The soil of experiment I was taken from a permanent pasture with a high total porosity of 52.4%, the soil of experiment II was taken from a field which had been under continuous cultivation for a long time with a total porosity of 45.3% and the soil of experiment III was taken from a recently cleared shelterbelt with a total porosity of 50.2%. Because of their reasonably high porosities, the three soils were expected to be uncompacted in their original state, but as will be shown, the soil of experiment II appeared to have been already compacted in its field condition, yet the experiment was carried to the end.

Effect of compaction on soil-water relationships

In the three experiments, the soils were compacted at moisture contents within that of their available range, but near to the field capacity moisture content. At such moisture contents, the pores which hold water in the available range are expected to be full, or nearly full, of water which, in its liquid phase, is not compressible, hence these pores are not affected by compaction, as, by definition (see definition of compaction in the review of literature and Soane, 1970,a), compaction is supposed to cause no change in the moisture content (weight basis) of the soil. However, the pores which are too large to hold available water are actually air-filled at such moisture contents and their individual volumes may be reduced by compaction to the size range holding available water. There would, thus, be a resultant decrease in the total porosity, but an increase in the total volume of water holding pores per unit weight of dry soil and consequently an increase in the available water capacity (AWC) of the soil. This hypothesis was tested, for the three experiments, from the soil moisture characteristic curves.

Experiment I. The soil was compacted at two moisture contents, these were (1) 23% which is less than that of the field capacity (100 cm suction) of the soil before compaction and (2) 31% which is that of field capacity. These two levels of compaction were given the symbols C1 and C2 respectively.

The C1 level of compaction showed increases, frequently significant (* to ***) in the percentage of water retained by the aggregates at all tensions in the pF range 1.0 - 3.7 in the small aggregate size range, 0.5-4.8 mm (A1) and in the pF range 1.0 - 3.2 in the large aggregate-size range, 0.5 - 6.3 mm (A2) (Figs. 19 and 20). These pF ranges represent the major part of the soil moisture characteristic where water is available for plants. The resultant increase by C1 level of compaction in the AWC in the small aggregate size range was 22.7% and in the large aggregate size range was 5.6%. The effect of compaction was less apparent in the large aggregate size range probably because of more inter (between)-aggregate water holding pores produced by closer packing which at pF 1 have overshadowed the effect of the differentiation in the intra (within)-aggregate water holding pores caused by compaction. At higher suctions, i.e. pF 1.7 to 2.0, where the contribution of the inter-aggregate water holding pores is expected to be less marked, the effect of compaction was more detectable.

However, at very high tensions, i.e. pF 4.2, compaction has resulted in slight decreases in the percentage of water retained in the aggregates probably because compaction has distorted the pores which hold water at high tension as a result of unavoidable mass-flow of soil particles. Nevertheless, at such high tensions, the texture of the soil, and not the structure, is the major factor in determining the percentage of water retained by the soil. This phenomenon was noticed at the C2 level of compaction and also resulting from compaction of the soil in experiment III and will not be dealt with any more.

When the available water at specific tensions, within the available range, was calculated as percentage of the AWC of the non-compacted soil (Fig. 22), the data showed that the C1 level of compaction has consistently resulted in marked increases in the available water. Increases were more marked, especially at low tensions where the water is more easily available for use by plants, considering the theory of "decreased availability" as moisture content of the soil approaches the permanent wilting percentage.

The C2 level of compaction also showed similar effects, as those of the C1 level of compaction, but much less markedly. In the small aggregate size range (A1), moisture content of the soil was increased by compaction in the pF range of 1.0 - 2.0 only. At pF values greater than 2, compaction actually reduced the percentage of water retained by the soil with the resultant increase in the AWC being only 15.4%. In the large aggregate-size range (A2), only at pF 1.7 and 2.0, did compaction increase the percentage of water retained by the aggregates with a nil resultant effect on the AWC. In the case of C2 level of compaction, because of the high moisture content of the soil at the time of compaction and also because the bulk of the soil was not in fact properly confined when compacted, the actual action of the applied force might have resulted in more mass flow of the soil particles than in compaction. Yet at specific tensions the available water, calculated in the same way as for C1, was increased (Fig. 22), but less markedly than by C1. This was more apparent at high tensions than at low tensions.

The overall effect of compaction, especially when the C1 level of compaction is considered, confirms the hypothesis, mentioned earlier, that controlled compaction could increase the AWC of the soil, through increasing the total volume of the available water holding pores. Similar effects of compaction, but on the bulk of the soil and not on the aggregates alone, have been reported by Jamison (1953), Hill and Summer (1967), Yang and de Jong (1971), Archer and Smith (1972) and Reeve et al (1973).

The effect of compaction on pore-size distribution is in fact not worth discussing as the data (see Figs. 21 and 22) were computed from those of the soil moisture characteristic curves. Any such discussion, however, would be similar to that on the retainability of water but in different units.

Inter-aggregate and intra-aggregate porosity make up the total porosity, with the major part being that of the inter-aggregate porosity. In this work (all the experiments) the inter-aggregate porosity was re-established by packing in the same way (unless stated as in the case of experiment II) of aggregates of specific size ranges. The effect of compaction, therefore, will be that on the intra-aggregate porosity only, and the effect on the overall structure will be comparatively small. The subject, however, will be discussed under the heading of aeration.

Experiment II. Although the soil was compacted at 21% moisture content which is well below that of field capacity, the soil moisture characteristic curves (Fig. 35) showed only small effects of compaction. The effect at low tensions, < pF 3.0 was slight decreases in the percentage of water retained by the soil, but at high tensions, > pF 3.0, very slight increases were recorded with a resultant 6% decrease in the AWC of the soil. The fact that compaction did not alter markedly the soil moisture characteristic curve at tensions greater than pF 2.0 indicates that the soil was already compacted in the field as a result of continuous arable use for a long period. The effect of this "field compaction", even though not clearly reflected in the field total porosity (45.3%) because of a recent cultivation, was very marked in the intra-aggregate porosity. Currie (1966) stated that inter-"crumb" porosity is a measure of the state of cultivation, while intra-aggregate porosity is the result of long term management practices, and gave examples to show that any given total porosity can arise from different pore distributions.

In this experiment the usefulness of the applicability of the soil moisture characteristics data was limited to the open packing (see Methods and Materials) only, because only in this packing was there a satisfactory similarity between the way the aggregates were packed in the pots, for the glasshouse experiment, and that in the devices which were used for the soil moisture characteristic curve determinations. However, the soil moisture data from the experiment did show the reducing effects of compaction on AWC, in all three packings, and also showed that in both close packing and packing with sand the AWC of the soils were only slightly increased by denser packing when compared with that of open packing (See Table 8).

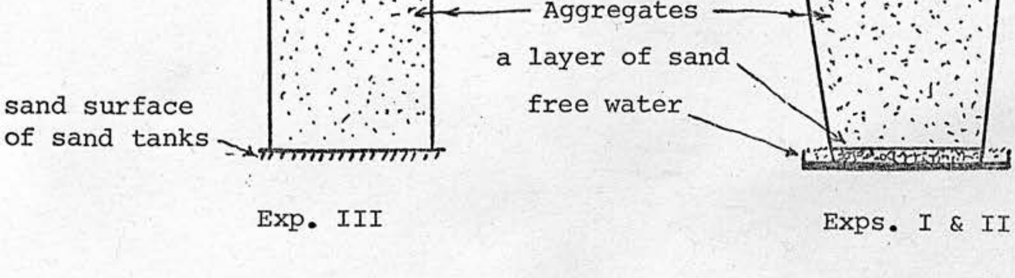
<u>Experiment III.</u> The soil was compacted at 27% moisture content, which is again well below that of field capacity. The effect of compaction, in the two discrete aggregate-size ranges used in the pot experiment, namely, the small aggregates, 0.5 - 4.8 mm (A1) and the large aggregates, 4.8-9.5 mm (A2), on the soil moisture characteristic curve was pronounced (Figs. 51 and 52) as well as on the pore-size distribution (Fig. 53). It is interesting to notice that in both the compacted and the non-compacted aggregates, the AWC of the soil is higher in the small aggregates than in the large aggregates. This difference apparently arose from more inter-aggregate water holding pores in the small than in the large aggregates.

In the small aggregates, the effect of compaction on the AWC, which was an increase of 23%, was more pronounced than in the large aggregates, where the increase was 12%. However, in the large aggregates the 12% higher AWC in the compacted soil over the non-compacted soil is more attributable to the actual effect of compaction than the 23% in case of the small aggregates as it is less confounded with the effect of the inter-aggregate water holding pores. The effect of compaction on the available water at specific tensions was also marked, especially at low tensions (Fig. 54).

In summary, the objective of compacting the soil in a manner to reduce the volume of the pores, which are too large to retain available water at field capacity, to the size range which hold the available water, was satisfactorily achieved in experiments I and III. In experiment II the failure in achieving this objective was because the soil was already compacted in its field condition.

Effect of compaction on soil-water-plant relationships

In the pot experiments, in order to isolate the effect of compaction on soil-water-plant relationships, from its effects on other factors of soil-plant relationships, aggregates of specific size ranges were used in systems of pots as shown below.



Exp. III

Exps. I & II

The sand layer was established (experiments I and II only) to reduce water logging, and the mulch layer was established (all experiments) to minimize direct evaporation from the soil. Therefore when watering was withdrawn (experiments I and II) or when a stress was applied (experiment III) the plants were using the water retained by the soil, and the retained water was mainly used for evapotranspiration, i.e. growth.

Control of the effects of compaction on other factors

In the three experiments, the other soil plant relationships were standardized, to a large degree, between "systems" of compacted and non-compacted aggregates because:

1. Aeration, which depends mainly on the macro-pores and the degree of saturation, was expected to be of the same magnitude, as the established macro-structure was made up of the same aggregate size range. However, inasmuch as the degree of saturation was the controlling factor, although the same levels of stress were established in all the appropriate pots, the differential intra-aggregate porosity of compacted and non-compacted aggregates resulted in marked differences in the degree of saturation especially at low tensions, where the degree of saturation is high and the air capacity is low. In the compacted aggregates, as the pores which at field capacity were air-filled pores before compaction, but their volumes were reduced to water holding pores by compaction, marked decreases in the air capacity were recorded. These decreases were progressively more detectable as tensions approached pF 1 in experiments I and III (see Figs. 23 and 55) where soil compaction was effectively achieved. It is interesting to note that the differential inter-aggregate micro-pores, resulting from differences in the aggregate size ranges, again in experiments I and III, had also marked effects on the air capacity of the soil at low tensions.

The data of the effect of compaction, through altering intra-aggregate porosity, on aeration at low tensions, is in fact an additional support to the hypothesis that controlled compaction of uncompacted soils results in reducing the volume of large pores (on volume basis v/v and after considering the reduction in the bulk volume of soil) to the range of water holding pores.

Only in experiments I and II, and then only at pF 1, was the air capacity of the soil below the 10% level, often quoted as the level below which plant growth is adversely affected. pF 1, in both experiments, corresponds to the soil water stress throughout the period of the experiments under continuous watering regime and to the period prior to discontinuing watering, which was most of the growing period, under watering withdrawal regime.

In experiment I, only in the large aggregate-size range was the air capacity below the critical 10% level regardless of the effect of compaction. Nevertheless, in the pots of the compacted aggregates the levels were slightly more further below 10% (6.8% for C1 and 7.3% for C2) than those of the non-compacted aggregates (8.3%). The effect of low air capacity had resulted in a lower yield (both fresh matter and dry matter) in the large aggregate size range than in the narrow aggregate size range irrespective of compaction and watering. In experiment II only in the dense packings (close packing and packing with sand) was the air capacity of the soils slightly below the 10% level regardless of the effect of compaction which, however, was very little. The yield, taken broadly, did not show any adverse effects of reduced aeration, probably being counter-balanced by slight increases in the AWC as a result of denser packing. In experiment III, the air capacity of the soil even though it was reduced by compaction, especially at low tensions, was always well above the 10% level. In fact when the mean effect of the two tensions was considered, both fresh matter yields and dry matter yields were identical in both aggregate size ranges at either level of compaction (see Figs. 65, IV and 69, IV), suggesting that between different compaction levels, aeration was not differentially restricting plant growth.

2. Root system ramifications were expected to be in the same manner in between the aggregates (see Plate IV), and any differences in root ramification caused by compaction would be, if at all, in that within the aggregates. It was not possible to make an accurate assessment of the degree of penetration of aggregates by roots although this was attempted. Nevertheless the visual evidence was that some roots penetrated into and through aggregates whether compacted or not.

3. Nutrient status of the soil was not expected to be affected by compaction in terms of "true availability". However, in terms of "accessibility" (Currie, 1970), the effect could be considered in two ways, these are: (1) in case of mass flow of mobile nutrients, the effect would be that on the case of water movement and is not a direct effect, and (2) in case of diffusion, where the effect would be more direct, within aggregates of the same size-range, the effect of compaction could be very little especially when the "small" size of the aggregates is brought into consideration. The concentration, in plant dry matter, of the nutrient elements N, P, K, Na, Ca and Mg was used as an indicator of the effects of compaction on the accessibility, to the root systems, of plant nutrients in the soil.

Despite the very satisfactory levels of available P and K in the soils used in the three experiments, many significant effects of treatments on nutrient concentration in plant dry matter were recorded, but an overall inspection of the whole data shows that in no case did the concentration of N, P, K, Ca or Mg approach levels commonly accepted as being associated with deficiency conditions in the plant, (Wallace, 1961).

Over all samplings, the range of concentration of the nutrient concentration in dry matter is shown in Table for the three experiments. The lowest approach to a "deficiency" level was for P in experiment III, when a value of 0.13% was recorded. The data of Table15 also show that the "lowest" and "Highest" values in three experiments were roughly evenly divided between compacted and non-compacted treatments.

Table 15. Lowest and highest levels of nutrient concentration (%)* in plant dry matter over all samplings for the three experiments.

nutrient elements	Experiment I		Experiment II		Experiment III	
	lowest	highest	lowest	highest	lowest	highest
N	2.80 ** (CO WO A1)S4	4.26 (CO WO A2)S2	2.77 (CO W1 PO)S6	4.08 (CO W1 PO)S2	2.46 (C1 A2 T100)S5	3.58 (C1 A2 T100)S1
P	0.24 (CO WO A1)S4	0.38 (C2 W1 A2)S2	0.21 (CO W1 PO)S6	0.41 (CO W1 PO)S1	0.13 (CO A2 T50)S5	0.24 (CO A1 T100)S1
K	3.74 (CO W1 A2)S3	4.64 (CO W1 A1)S5	2.43 (CO W1 PO)S6	4.47 (C1 WO PC)S1	2.24 (C1 A2 T50)S5	4.43 (CO A2 T100)S2
Ca	1.75 (C1 WO A2)S2	2.25 (C1 W1 A2)S3	1.86 (CO W1 PS)S6	3.11 (CO W1 PC)S1	1.86 (C1 A2 T100)S5	2.54 (C1 A2 T50)S2
Mg	0.39 (C1 W1 A2)S2	0.53 (CO WO A1)S3	0.39 (C1 W1 PO)S6	0.61 (C1 W1 PO)S1	0.36 (C1 A1 + A2 T50)S5	0.56 (C1 A2 T100)S1

* Na concentrations were very erratic and were probably best ignored as being irrelevant to the yield data.

** The treatment and sampling at which the value is recorded.

The data of Table 15 infer that no serious restriction of yield can have occurred as a result of deficiency of the nutrients determined. It is not, however, possible to state categorically that yields were never affected by the effects of treatments on nutrient concentration. Although effects of compaction, aggregate-size range and watering regime on the concentration of various nutrients in plant dry matter were often significant, and sometimes highly so, it would be fair to say that the differences were usually quite small and the precision of the statistical and chemical analyses have demonstrated significance, for example between such concentrations as:

- from 3.26% to 3.65% (***) for N as a main effect of C2 level of compaction at sampling 3 in experiment I.
- from 0.183% to 0.175% (***) for P as a main effect of the aggregate size range in experiment III.

or from 3.40% to 3.18% (***) for K as a main effect of compaction in the small aggregates in experiment III.

Perhaps more interesting are the consistent effects of treatments, over the various samplings, on nutrient concentration in dry matter. However, only in a few instances were such consistent effects of compaction recorded, such as in the case of Mg in experiment I, where both levels of compaction consistently depressed the concentration in the large aggregate size range under both watering regimes and in the narrow aggregate size range under continuous watering; and in experiment III, where Mg concentration was again consistently reduced in the small aggregates under 100 cm tension and in the large aggregates under 50 cm tension. In experiment III similar effects of compaction, i.e. consistent depression, were recorded for Ca and K in the small aggregates under 100 cm tension.

One of the measures taken to reduce the effect of compaction in these experiments was to use aggregates of relatively small sizes from which the accessibility of nutrients would be less restricted than in larger aggregates. The evidence from the concentration of nutrients in dry matter, taken broadly, indicates that the more mobile elements K, Na and to a lesser extent, Ca, were unaffected by aggregate size. However in experiment III, in which no nutrients were added, the uptake of less mobile nutrients such as P, was highly significantly reduced in the larger aggregates and a similar effect occurred with Mg (also not added) in experiment I.

In all the experiments, it was regarded as extremely important to avoid yield restriction by lack of N, and in fact this was one of the reasons for the essential choice of red clover as a test crop. All visual observations of above soil tissues suggested no differences in greenness of plants and where inspection was possible, modulation appeared satisfactory. However, there was a tendency, especially in experiment III for compaction to reduce N concentration in the plants. This, and similar cases of other nutrients, was probably a result of the more vigorous growth of plants in compacted soil giving a dilution effect of the nutrient. There were no consistent trends in the effects of compaction on the concentration of P, K, Ca or Mg in plant dry matter.

In summary, it could be concluded from the evidence from the three experiments that, although compaction may adversely affect the nutrient status of the soil, in the present work, the effect, by aid of the design, was reduced to a level at which the plant growth was not restricted.

4. The effect of compaction on the thermal properties of the soil was not expected to have influenced the growth of plants in the three experiments because the sizes of the pots were relatively small and the

experiments were carried out in the glass house (with the exception of the experiment I at early stages where it was in a cage) in which temperature fluctuation was very little, and the treatments were satisfactorily randomized.

The Yield

As has been shown in the foregoing discussion, the experimental procedures have permitted, to a satisfactory extent, the isolation of compaction effects on the availability of water to plants from those on aeration, mechanical impedance, nutrient status and thermal properties of the soil. The differential responses of the yield may, therefore, mainly be related to the effect of compaction on the availability of water for plants. In fact, if the other factors mentioned above had not been satisfactorily controlled, their expected effects would be in favour of the non-compacted soil, i.e. yields would have been reduced by compaction. The general increases in yield caused by compaction may, therefore, be interpreted as the positive effects on availability of water minus any negative effects arising from the other factors. The effects, through water availability, of compaction on yield shown, for example in Figs. 31, 33, 63 and 67, may, therefore, be regarded as minimal effects.

Yield and the availability of soil water. Richards and Wadleigh (1952), in discussing the influence of soil moisture on the vegetative growth of plants, stated that growth represents the efficiency with which additional dry matter is produced in the leaf area within which photosynthesis may take place, and that growth analysis provides a direct basis for evaluating yield response to treatment and/or environment. A detailed discussion by Slatyer (1967) on the relationships between growth, plant-water stress and soil-water stress reveals evidence that growth, i.e. gain in dry matter weight, ceases when photosynthesis drops, as a result of increased plant-water stress (≈ soil-water stress), to a level which is equal to, or less than, that of respiratory losses (Fig. 71).

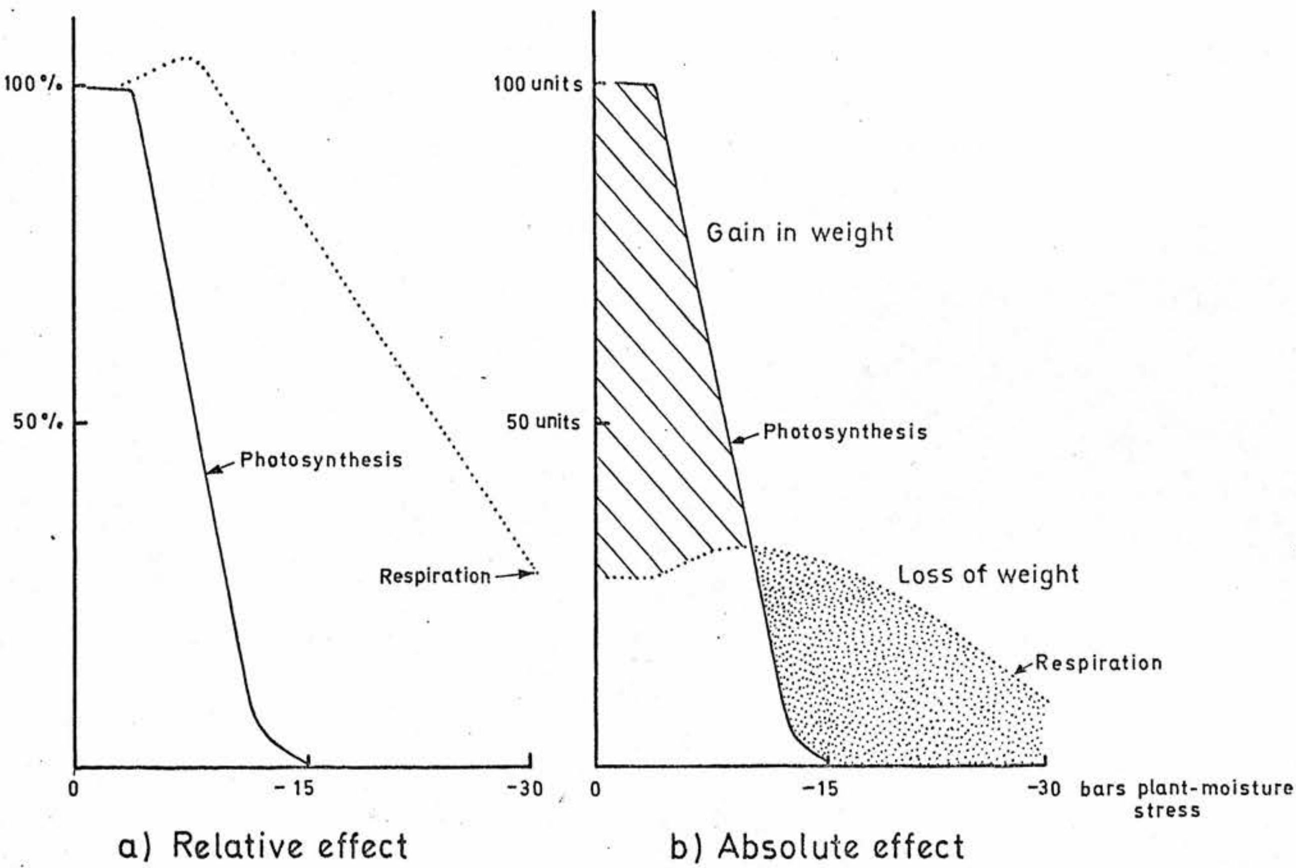


Fig. 71. Changes in Photosynthesis and respiration as plant-water stress increases (quoted from Agricultural Development Association course on Irrigation of farm crops at the University of Reading, 14-16th December, 1970).

In this work, as a result of homogeneity of the soil in the pots, the soil water stress, i.e. matric potential, was always a function of the moisture content only (Swartzendruber, 1966). Both the AWC and the available water at any specific tension within most of the available range were increased by compaction in experiments I and III. However, according to Richards (1928), the velocity with which the soil water moves to replace that which has been used, should also be considered as an important factor in evaluating the actual availability of soil water to plants. The effect of compaction on this factor, i.e. on the unsaturated hydraulic conductivity of the soil, has not, in this work, actually been measured by laboratory methods. Nevertheless, it is safe to state that as the percent of water holding pores, against any tension within the available range, is increased by compaction, i.e. percent of water conducting pores is also increased (Marshall, 1950). The unsaturated hydraulic conductivity, therefore must have increased by compaction. In yield response studies, however, the separation of the capacity factor (quantity) from the dynamic factor (ease of movement) is found to be difficult (Peters, 1957).

The yield responses.

Experiment I. Under both watering regimes (continued and withdrawn) both fresh matter and dry matter yields responded, often significantly especially at later samplings, to the effects of the C1 level of compaction on the AWC of the soil in both aggregate size ranges. The yield responses to the C2 level of compaction, which was less effective, were smaller.

Taking the continuous watering regime (W1), where the soil-water stress was continuously very low (pF 1), both fresh matter yield (Fig. 31 and dry matter yield (Fig. 33) showed marked responses to the C1 level of compaction, in both aggregate size ranges. Both yields increased progressively from sampling to sampling up to sampling 3 in the small aggregate size range (A1) and up to sampling 5 in the large aggregate size range (A2). The overall yield in the large aggregate size range (A2) was less than that in the small aggregate size range (A1). The possible reason for this has already been given as reduced aeration (air capacity less than the critical 10% level) in the large aggregate size range. In the small aggregate size range (A1) where the growth was in general high, the response to the C1 level of compaction was progressively more marked until sampling 3, after which, i.e. samplings 4 and 5, the response almost ceased, probably because root systems, as had been noticed, reached the free water in the lower parts of the pots and the saucers, where the availability of water was equal for the plants in all treatments. It is, however, interesting to notice that the dry matter yield showed better responses than the fresh matter yield, especially at early samplings. This was reflected in the percent dry matter data (Fig. 34) which show that percent dry matter was slightly higher in the compacted soil, and in fact, indicate that growth was faster in the compacted soils. Thus the plants in compacted soils tended to be a "stage" ahead of those in non-compacted soils. This would result in a higher proportion of stem to leaf, and hence to a higher percentage of dry matter. The C2 level of compaction, over all samplings, showed either no, or slight effects. However, the noticeable effects of the C2 level of compaction were slight decreases, especially at sampling in the small aggregate size range (A1), which could be related to the true availability of water; and slight increases, especially at later samplings, in the large aggregate size range (A2), which could be a result of better aeration in C2 than in the non-compacted soils (See Fig. 22).

When taking the watering withdrawal regime (WO), again the effect of the C1 level of compaction was marked in both the fresh matter yield (Fig. 30) and the dry matter yield (Fig. 32). The fresh matter yield at sampling 1, which was 3 days after the watering withdrawal, showed no more effects than what has been discussed under the continuous watering regime. It was between samplings 1 and 2 when the plants' source of water was restricted to what was retained by the soils (AWC). In this period the yield showed marked responses to the C1 level of compaction. In fact after sampling 2, wilting had started in C1 compacted soils while it started in both C2 compaction and the non-compacted soil (CO) after sampling 3. Indicating that the total leaf surface area (evapotranspiration) was greater in C1 than in C2 and CO. This was most probably due to more, and more easily, available water. The effect of aggregate size range on the yield was, in general, similar to that under continuous watering. However, after wilting, which started at different times and occurred to different extents at different samplings in the 3 soils, a discussion of the fresh matter yield data would not be rewarding and the dry matter yield data are more interesting.

The dry matter yield, in both aggregate size ranges, showed a consistent response to the C1 level of compaction. The greatest responses were at S2 which represents the maximum use of the available water by the plants in the C1 level of compaction. Between S2 and S4, the growth was faster in the non-compacted soil, because the plants were smaller and used the available water in a longer period. At sampling 5, where the growth was expected to have eventually ceased, the C1 level of compaction showed the highest yield. In the C2 level of compaction, as a result of the slow rate of growth at early samplings because of the reduced aeration, the available water was transpired in a longer period, but eventually the total yield was less, at sampling 5, than in the other two soils. In the large aggregate size range, the fast growth between samplings 2 and 3 is probably due to restoring a good level of aeration which was depressed before watering withdrawal.

Although growth was retarded after sampling 2 in the C1 compacted soil and after sampling 3 in both C2 compacted and non-compacted soils, it had not actually ceased even at sampling 5. This, frequently observed phenomenon (stress retarding growth, but growth not halted until permanent wilting occurs) has been explained (Slatyer, 1967) in the view of diurnal changes in plant-water stress (Fig. 72) caused by relative rates of daily transpiration and absorption.

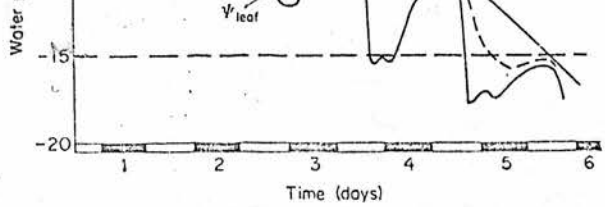


Figure 72. Schematic representation of leaf-water potential (ψ leaf), root surface-water potential (ψ root) and soil-water potential (ψ soil) relationships as transpiration proceeds from a plant rooted in initially wet soil (After Slatyer, 1967).

As the soil dries, a level of stress will initially be imposed on the plant tissues by the soil-water stress, which results in temporary wilting in daytime and recovery of turgidity at night, which tend to supress metabolism during the diurnal period of maximum water deficit, hence an initial reduction in the rate of growth. With time, the period of stress becomes progressively longer day after day and the rate of reduction in the growth rate accelerates till permanent wilting occurs. In fact a comparison of soil water data of Tables and show that the actual permanent wilting percentage was approached towards sampling 5.

In experiment II, where compaction slightly reduced the AWC of the soil, the fresh matter yield, under continuous watering was reduced by compaction in open packing (Fig. 44) especially at S5, but it was slightly increased by compaction in close packing and packing especially at later samplings with the main effect of compaction being slight reductions in the both fresh and dry matter yields under both watering regimes (Figs. 47 and 49) except a slight increase in the fresh matter yield under continuous watering.

The main effect of packing, which in this experiment was used as a means of increasing the total volume of water holding pores (inter-aggregate water holding pores) was not clearly detected. Both close packing and packing with sand resulted in considerable reduction (see Fig. 37) in the air capacity of the soil in the pots (air capacities were less than the critical 10% level at pF 1 in both packings), yet the yield under neither watering regimes was adversely affected. However, the effects of the two dense levels of packings (close packing and packing with sand) were not assessed by laboratory methods because of the difficulties in producing the same levels of packing in the devices used for the soil moisture characteristic curves. Nevertheless, the determination of the moisture contents of the soils after each sampling showed slight increases resulting from these two levels of packing. The fact that the yield did not show any detectable main effect of packing, was therefore, related to the possibility of counterbalancing the two opposite effects of packing, namely on aeration and water availability. In the compacted aggregates, as the pores which at field capacity were air-filled pores before compaction, but their volumes were reduced to water holding pores by compaction, marked decreases in the air capacity were recorded. These decreases were progressively more detectable as tensions approached pF 1 in experiments I and III where compaction effectively was achieved.

A conclusion from experiments I and II. On the one hand, experiments I and II showed that the availability of water for plants in uncompacted soils may be increased by controlled compaction. On the other hand, in experiment I, where the soil, at its field condition, was uncompacted, and compaction positively affected the availability of its water to plants (in laboratory tests), the pot experiment showed only little effects of the increased availability of water on the growth of the test plant. The differential yield responses, to compacted and non-compacted soils, was not easily detectable probably because of the proportionally large plant mass to soil mass ratio. However, 6 plants per pot were considered necessary in order to eliminate the effect of the natural variation in the plant size on the final yield, and the use of larger pots was not practically possible. Therefore, in order to achieve a detectable differential response of the yield to the variation, caused by compaction, in the availability of soil water for plants, without risking the danger of fewer plants per pot or the practicality of the experimental work, a special approach was made in experiment III.

Experiment III. In contrast to experiment I and II, in this experiment the main objective of the investigation was approached (see Methods and Materials) by:

1. Applying more than one period of stress, by which the effects of the variation in soil-water availability for the plants are exaggerated (cumulative effect) in a number of "stress-applied, stress-released" cycles.

2. Maximizing the use of the available water by plants, i.e. minimizing the length of periods where "excess water" was additionally available for the plants. At the end of each stress-applied period, i.e. when an arbitrary level of wilting occurred, the tension was rapidly reduced to zero at the sand surface in the tanks, the pots rapidly rewetted, and then, after full recovery from wilting, the tension was reduced to near 50 cm or 100 cm. (T 50 & T100).

Therefore, the AWC for the soils under 100 cm tension treatment is that fraction of the moisture percentages retained between pF 2.0 (0.1 bar) and pF 4.2 (15 bar) and for those under 50 cm tension treatment that between pF 1.7 (0.05 bar) and pF 4.2. This, in fact, means higher AWC under 50 cm tension than under 100 cm tension.

The aggregate size range did not show any marked "main" effect on either fresh matter yield or dry matter yield. However, taking the mean of all samplings, the fresh matter yield responded very slightly to the large aggregates over the small aggregates (Fig. 65,III), but the dry matter yield responded, again very slightly to the small aggregates over the large aggregates (Fig. 69,III). Both fresh matter and dry matter yields were higher under 50 cm tension than under 100 cm tension, indicating, in fact, the sensitivity of the test plant (red clover) to the availability of water, and the efficiency of the system, in regulating the amount of the available water. There was a significant interaction between the aggregate size range and tension. This interaction (see

Fig. 69, ~~IV~~ VI for D.M.), which took the form of higher yield (both fresh matter and dry matter) in the small aggregates under 100 cm tension, but in the large aggregates under 50 cm tension, indicates that the effect of inter-aggregate water holding pores could be significant when a high tension, such as 100 cm, is applied. In the small aggregates (where more inter-aggregate water holding pores are expected to be established than in the large aggregates) the yield was markedly higher than in the large aggregates under 100 cm tension, while under 50 cm tension, where proportionally more inter-aggregate pores hold water, the effect of the aggregate size range was less marked on the yield.

Compaction, irrespective of the aggregate size range and tension showed marked effects on both the fresh matter yield (Fig. 62) and the dry matter yield (Fig. 66). Taking the mean effects of the aggregate size range (which had no effect) and the tension both yields responded to compaction progressively more markedly sampling after sampling with the responses being highly significant at sampling 2 and onwards (Figs. 63, for fresh matter, and 67 for dry matter). However, when the two tensions were considered separately, taking the mean effect of the aggregate size range, and the mean of all samplings, both yields (Figs. 65, V for fresh matter and 69, V for dry matter) showed that the effect of compaction was slightly more marked under 100 cm tension than under 50 cm tension. This, in fact, indicates that compaction had a considerable effect on the intra-aggregate pores, which are the major component of the pores that hold water under the higher tension, i.e. 100 cm tension, while under 50 cm tension, as a result of a greater contribution of the inter-aggregate water holding pores to the AWC, the effect of compaction was less markedly reflected in the AWC, through affecting the intra-aggregate water-holding pores. Consequently there was a less marked response of the yield to compaction than under 100 cm tension when taking the samplings individually, both fresh matter yield (Fig. 64) and dry matter yield (Fig. 68) showed considerable responses to compaction under both tensions. Highest responses, for the two tensions occurred alternately over the 5 samplings. This, in fact, gave rise to a significant (**) interaction between sampling, compaction and tension. The reason for this special pattern of interaction may be as follows: as after cycle 1 most of the wilted plants (stress was released and the soils rewetted when the plants in about 50% of all the pots irrespective of treatments were wilting) were in the 100 cm tension treatment, because of higher tension and lower relative AWC, by the start of cycle 2, the plants, under 50 cm tension were proportionally large as they suffered less wilting during cycle 1 because of a shorter period of high stress. By the end of stress-applied period of cycle 2 most of the wilted plants were this time in the 50 cm tension treatment, because, despite lower tension and a higher relative AWC, the plants were proportionally large in the 50 cm tension treatment and transpired the available water in a short time. Therefore by the start of cycle 3, the plants were once more proportionally large in the 100 cm tension treatment and by the end of stress applied period of cycle 3 the wilted plants were mainly in the 100 cm tension treatment and so on. This effect was observed visually but was not expected to be reflected so well in the yield data. Sampling 1 was carried out when the plants recovered from wilting after the stress of cycle 3 was released. At this sampling the effect of compaction was at a low level in the 100 cm tension treatment but at a high level in the 50 cm tension treatment, which coincides with the sequences mentioned above.

The foregoing discussion, in addition to the directly interesting points, indirectly shows the sensitivity of the plants to the watering regime and the efficiency of the experimental procedures.

The percent dry matter data showed a significant effect of compaction. Compaction at all the individual samplings, when the mean effects of tension and aggregate size range were taken (Fig. 70,a) and when the means of all samplings were taken under each of the two other treatments separately (Fig. 70,b) resulted in a higher percentage of dry matter, indicating, as in experiment I, that growth was a "stage" ahead of the non-compacted soil and a higher percent dry matter has resulted from a proportionally higher stem/leaf ratio.

<u>The supplementary experiment.</u> The results of this supplementary experiment, where one design unit only (16 pots) was used and the plants were allowed to grow under continuous watering, with a very low tension, under the same conditions of the major experiment till sampling 5, show that both fresh matter and dry matter yields responded to the compaction, but comparatively to a much lesser extent than the responses in the major experiment.

GENERAL DISCUSSION

In the three experiments the effects of compaction on mechanical impedance, nutrient status, aeration and thermal properties of the soil were satisfactorily controlled. The differential responses of growth (yield) under the watering regime treatments were, therefore, mainly related to the effects of compaction on soil-water-plant relationships.

In experiment I, in the narrow aggregate size range, the response of the yield to the C1 level of compaction, under watering withdrawal treatment, was rather small despite the fact that laboratory tests showed marked increases in the AWC of the soil by compaction. The reason was primarily a high plant mass to soil mass ratio. However, under continuous watering regime, the yield also responded to compaction, but comparing the rate of growth during the period when, under watering withdrawal regime, the AWC of the soil was the only source of the available water for use by the plants (i.e. between sampling 1 and permanent wilting), shows that the response of the yield to compaction was comparatively greater when watering was withdrawn than when it was continuous. This differential response of growth is attributed to the differential AWC of the soils caused by compaction. In other words, the effect of compaction on the availability of water, especially the capacity factor (AWC) was reflected in the yield under the watering withdrawal regime. The other important factor in determining the availability of water for plants, namely the ease of its movement towards plant roots (the dynamic factor) was better reflected in the yield responses under continuous watering. Under continuous watering, where adequate amounts of water were continuously "available", the growth response is related to the ease of water movement from various points in the soil towards the root surfaces in order to counterbalance the progressively increased stress along the water pathway from the soil to the transpiration active sites of the plants.

In the C2 level of compaction, where laboratory tests showed less marked effects of compaction on the AWC of the soil, less marked responses of the yield were recorded under both watering regimes.

In the large aggregate size range, the air capacity of the soil, irrespective of compaction levels, was reduced to less than the critical 10% level, throughout the period of the experiment under the continuous watering regime and, under watering withdrawal regime, during the 6 week period prior to the withdrawal of watering. The effect of this inadequate aeration was reflected in the overall growth. Yet effects of compaction, especially of the C1 level, were detected. It is interesting to notice that, after the withdrawal of watering, the growth immediately responded to the restored aeration indicating that the inadequate aeration had suppressed the growth.

In experiment II, where one level of compaction was made, but both compacted and non-compacted aggregates were packed at three different "packing" levels. Compaction, in general, had negative effects on the AWC of the soil and consequently on the yield. This was because the soil, in its field condition, was already compacted and the attempted compaction for the purpose of the experiment actually resulted in a reduction in the AWC of the soil, probably caused by mass flow and the expulsion of water during compaction. The two levels of dense packing, namely close packing and packing with sand were expected to result in increases, when compared with open packing, in both the AWC and the unsaturated hydraulic conductivity of the soil because of the extra inter-aggregate water holding pores. However, as actual measurements showed they resulted in reductions in the air capacity of the soil to slightly less than the critical 10% level and the two effects probably counterbalanced each other as the resultant effect of packing on the yield was nil.

In experiment III, where compaction, as in experiment I, markedly increased the AWC of the soil, marked responses of the yield to compaction were recorded. This, in fact, was partly related to the sophisticated experimental procedures by which the consequences of effects of compaction on the availability of water for plants on the growth were exaggerated. In this experiment, the use of the available water of the soil by the plants was strictly controlled. In experiments I and II, the only means of controlling the quantity of "available water" for the plant under water withdrawal was the removal of the watering saucers. This had several disadvantages:

1. At this stage the soil water would be at a very low tension ($\approx$ 10 cm) and the effective field capacity moisture content would thus be higher than that in the field.
2. The excess water was removed over a long period, i.e. plants used excess water for some time before they actually became dependent on the "AWC" water.
3. Only one period of stress was used, i.e. from full turgidity to permanent wilting, during which the variation in AWC between compacted and non-compacted aggregates was not clearly reflected in the growth because of the high plant-mass to soil-mass ratio.

In experiment III, the first and the second disadvantages of the procedures of experiments I and II, mentioned above, were overcome by the use of specially constructed sand tanks by means of which; (1) tensions near to 50 cm and 100 cm water, which cover a range within which the actual field capacity of the soil is more likely to lie, were established, and (2) the excess water was removed in a reasonably short time. The third disadvantage was overcome by applying five stress-applied, stress-released cycles by means of which an exaggerated effect of the variation in the AWC was imposed on the plants to result in a cumulative effect on the yield.

Summary and Conclusions

A number of previous works have shown that compaction may increase the available water capacity (AWC) of the soil. Such effects of compaction would be expected in accord with its definition (the process of packing closer together the soil particles by an effective force exerted on the bulk of the soil with a resultant increase in the soils dry bulk density but no change in its moisture content). It is, in fact, the degree of "closer packing" which may result in the establishment of extra water holding pores and hence an increase in the AWC of the soil, which in turn depends on the degree of compaction. The degree of compaction is known to depend on force characteristics, soil properties and the moisture content of the soil at the time of compaction. When the moisture content of a soil is equal to, or less than, that of its field capacity, the available water holding pores will be full, or nearly full, of water, but the larger pores will be air-filled. If an uncompacted soil is effectively (suitable force and soil properties) compacted at such a moisture content, the individual volumes of the air filled pores would be reduced probably to the volume range of available water holding pores, but the originally existing water holding pores being occupied with water, which, in its liquid phase, is not compressable, would not be affected, with a resultant increase in the percentage of the water holding pores, i.e. the AWC of the soil.

To study these effects of compaction on the availability of soil water for plants, on the one hand, and to evaluate the consequent agronomic usefulness of such effects, on the other hand, were the main objectives of this research work.

Compaction, however, is known to affect, in addition to soil water, other soil-plant relationships, i.e. mechanical impedance, nutrient status of the soil, soil air and soil thermal properties, and the literature indicates, these important soil factors in plant growth interact with each other and the isolation of any one of them, for experimental purposes, is extremely difficult. In fact the surveyed literature in this work does not contain any work which relates the effects of compaction to plant growth through soil water alone. Nevertheless, it includes a number of works on the effect of compaction on the AWC of the soil as measured by empirical laboratory techniques. The isolation of the effects of compaction on soil water, from those on the other factors of soil-plant relationships, in pot experiments, was also an objective of this research work.

With these objectives in mind, one pilot and three major experiments were carried out in this investigation in 1971-1973, using one soil type (a clay loam) with three past histories and using red clover as the test crop.

The soils were chosen because of their suitable consistency and stable structure. Consistency is a major property of the soil which determines the degree of compaction, on which a degree of control was essential, i.e. controlled compaction. Stable structure, and hence pore volume stability insures the maintenance of the achieved degree of compaction, which also was of considerable importance in the experimental procedures.

Red clover was chosen, among three species known for their sensitivity to soil-water status, as a test crop in the pilot experiment. Furthermore, the use of this legume allowed the danger of nitrogen availability-soil structure interaction to be minimized.

In order to eliminate, or satisfactorily minimize, the effect of compaction on the soil-plant relationships other than soil water, artificially compacted and non-compacted soils were completely air dried, gently crushed and aggregates of specific size ranges were sieved out. These aggregates were used in both various physical property determinations and in the pot experiments. As the pots were filled, in the same standardized manners, with aggregates of the same specific size ranges, the effects of compaction on the structural properties of the soil were eliminated except for within the aggregates. The fact that the intra (within) aggregate porosity is of major importance in determining the AWC of the soil but was anticipated to be of less importance, especially in the relatively small aggregates used, for the other factors involved in soil-plant relationships, was the basis for concentrating the effects of compaction on soil-water-plant relationships and reducing the effects on the other soil-plant relationships in the three experiments. The results of the three experiments, indeed, showed satisfactory achievement of this purpose.

In experiment I, the soil (taken from a pasture) was compacted at two moisture content levels. These were high moisture content (field capacity) and low moisture content (below field capacity). Laboratory tests, (soil moisture characteristic curves), on the two aggregate size ranges (narrow and large) used in the pots, showed more marked effects of compaction on the AWC of the soil at the low moisture content than at the high moisture content. The response of clover in the pots, under both continued and discontinued watering regimes, was also more marked to compaction at low moisture content than at high moisture content. Under continuous watering, i.e. low stress, the yield response was attributed mainly to the effect of compaction on the ease of water movement in the soil (dynamic factor). Under discontinued watering by means of removing the watering saucers and drainage of gravitational water at an arbitrary stage of growth, i.e. eventual high stress, the plants at the later stage of growth depended on the "AWC" water. The yield response was, therefore, in addition to the dynamic factor prior to the watering withdrawal, partly related to the effect of compaction on the AWC of the soil (capacity factor). Evaluation of these two factors separately is extremely difficult and was not attempted.

In experiment II, the soil (taken from a field which had been under continuous cultivation for a long time) was compacted at one level of moisture content (below field capacity), but, as the laboratory tests showed, the soil was already compacted in its field conditions and the attempted compaction actually slightly reduced the AWC of the soil. The past history of the soil, i.e. land use system, is the only possible cause for the compaction. In the pots, compacted and non-compacted aggregates of one size range were packed at three levels, open packing, close packing (by means of vibration) and packing with sand (by filling the pores in between the aggregates with sand). The yield, under the same two watering regimes as described for experiment I, was slightly depressed as a main effect of compaction over the three packing levels. Although the denser levels of packing were expected to increase the AWC of the soil by producing more inter-aggregate water holding pores, they actually, as measurements confirmed, reduced the air capacity of the soils. These two factors counterbalanced each other resulting in a nil main effect of packing on the yield.

In experiment III, the soil (taken from a recently cleared shelterbelt) again was compacted at one level of moisture content, and two discrete aggregate size ranges (small and large) were used. Laboratory tests showed the effectiveness of compaction. To the soil water in the pots two levels of tension (50 cm and 100 cm water) were applied by means of four sand tanks which were specially constructed for this purpose (in contrast to the previous two experiments where it was created by removing the watering saucers only). This experiment also differed from the other two in that, instead of establishing one period of stress which ended with the permanent wilting of the plants, five successive periods of stress were established each being ended at an arbitrary level of wilting by rewatering till full recovery.

In the three experiments a layer of mulch was established on the top of the soil surface in the pots in order to minimize direct evaporation from the soil, i.e. maximum use of the retained water by the soil for evapotranspiration. In the three experiments, the results showed that the effects of compaction on root ramification (assessed by visual inspection), nutrient status of the soil (assessed from nutrient concentration in dry matter), aeration (assessed from measured values) and thermal properties of the soil (considered in the experimental procedures) were satisfactorily eliminated, inasmuch as yield would have been affected. The differential growth, assessed by both the yield (fresh and dry matter) and the stage of growth (% dry matter) was therefore related mainly to the effect of compaction on soil-water-plant relationships.

Conclusions

1. Compaction of three clay loam soils, from one soil series, by effective compactive forces at specific moisture contents within the available range, confirmed previous conclusions that compaction increases the available water capacity of soils which, in their original states are not compacted.

2. To achieve an increase in the AWC of the soil, compaction must increase the total volume of the water-holding pores per unit weight of the soil. Although theoretically field capacity moisture content seemed to be ideal for a maximum increase in the AWC, in practice it gave smaller increases than compaction at moisture contents slightly below field capacity. This was related to the occurrence of soil deformations other than compaction, such as mass-flow of soil particles and consequent reductions in water-holding pores, resulting from higher plasticity at higher moisture contents. Thus the moisture content of the soil, at

the time of compaction, plays a dual role in determining the magnitude of the achieved effect mentioned above.

3. The use of this particular clay loam had a number of advantages in this work:

   a) It is characterized by a consistency, which at the desired moisture contents, allowed satisfactory responses of the soil to the action of the applied force during compaction.

   b) The high structural stability ensured maintaining the achieved degree of compaction during various determinations of the physical properties of the soil, and more especially during the pot experiments as the specific size ranges of the aggregates had to be maintained.

4. Comparisons of soil moisture characteristic curves of compacted and non-compacted aggregates showed that,

   a) They are not only good indicators for assessing the magnitude of the increase in the AWC of the soil by compaction, for which values up to 20% were recorded, but also the manner of the distribution of this increase over the range of tensions at which soil water is available for use by plants.

   b) As the unsaturated hydraulic conductivity, at any tension, is a function of the moisture content of the soil at that particular tension (i.e. the water-filled pores are the conducting pores) the increase in the moisture content of the soil, at tensions where soil water is available for plants, also results in easier movement of the available water in the soil towards the roots.

   c) The lower limit of available water, i.e. permanent wilting percentage, is only very slightly affected by compaction, which agrees well with the accepted theory of the dependence of the lower limit on the texture more than on the structure of the soil.

d) It is the upper limit, i.e. field capacity, whichever acceptable arbitrary tension is considered, that is affected by compaction. In fact the soil moisture characteristic curves showed that the distribution of the increase in the AWC of the soil by compaction (see conclusion 4,a) is mainly concentrated at lower tensions, i.e. approaching field capacity.

The soil moisture characteristic curve, which in fact expresses, in different units, pore-size distribution of the soil, is therefore, a better indicator of compaction, than total porosity, as it provides a detailed, and not an overall, picture of the effect of compaction.

5. Calculation of pore-size distribution, from the soil moisture characteristic curves, showed that effective compaction results in an increase in the total volume of the water-holding pores per unit volume of bulk of the soil, but in a decrease in that of the larger pores. This actually means that the increase in the AWC of the soil is at the expense of its air capacity. If the latter is reduced to below critical levels for plant growth, and if not restored by an effective cultivation, plant growth would be adversely affected. This consequence of compaction and also those on the other factors of soil-plant relationships were anticipated and were fully considered in the pot experiments.

6. In the pot experiments, in order to concentrate on the effect of compaction on soil-water-plant relationships, and to reduce these effects on other soil-plant relationships, only aggregates of specific, relatively small, size ranges were used on the basis that the within-

aggregate porosity is of major importance in determining soil-water status in the available range, but is of less importance for the other factors, i.e. mechanical impedance, aeration, nutrient status and thermal properties of the soil. From the results of the pot experiments the following conclusions were made:

a) The effect of compaction on soil-water-plant relationships was satisfactorily isolated from those on the other soil-plant relationships by the use of relatively small aggregates only instead of the whole soil, and also by minimizing the N nutrition-soil structure interaction by the successful use of a legume, sensitive to the water availability, as test crop.

b) Irrespective of compaction, plant growth was adversely affected when the air capacity of the soil dropped to less than 10% level at low tensions.

c) Plant growth responded (10-15% increase in the dry matter yield) to the increase, by compaction, in the availability of soil water resulting from the increase of both the AWC of the soil (i.e. when a period of drought follows a wet period) and the unsaturated hydraulic conductivity (i.e. when soil water moves to replace that which has been used by plant roots).

7. In assessing the goodness of the experimental procedures the following points are worth mentioning:

a) The soil moisture characteristic curves gave values of the availability of soil water for plants at various tensions which were closely similar to those obtained from the determination of soil moisture content (experiments I and II) at successive samplings (from turgidity to permanent wilting) when the latter were related to the plant behaviour (growth curves) at these samplings. This indicates both the validity of the soil moisture characteristic curves for assessing the effect of compaction on soil-water availability for plants and the good control on the use of available water by plants in the experiments. In experiment III the degree of this control was further improved by applying more than one period of stress (cumulative effect of the increased AWC by compaction on plant growth) and by establishing tensions of 50 and 100 cm water (more realistic upper limits of available water for field conditions) by means of a series of sand tanks especially constructed for this purpose. In the sand tanks, sand particles of a specific size range were used in order to obtain maximum possible hydraulic conductivity of the critical sand layer in the tanks, which in addition to the advantage of establishing the desired tensions in the soil in the pots, had the advantage of removing the excess water from the soil in the pots in the shortest possible time (maximum restriction on the source of water for the plants to that of the available water of the soil).

b) Although the large pores in between the aggregates (whether compacted or not) were standardized, by the use of the same aggregate size range, at very low tensions, i.e. 10 cm water, where air capacity of the soil approaches critical levels, and hence becomes an important factor in plant growth, the variation, caused by compaction, in the within-aggregate pore system resulted in unavoidable differences in the air capacity between the compacted and non-compacted aggregates in experiments I and II. In experiment III, as very low tensions were not used, critical low levels of air capacity were not reached except at watering times. The effect of compaction on soil air was, therefore, only in experiment III completely eliminated.

c) Although the nutrient concentration in dry matter showed no deficiency of any of the important nutrient elements, only N level in the three experiments showed little or no effect of compaction. However, the reductions in other nutrient concentrations in dry matter were slight.

d) As the negative effects of compaction mentioned in 8,b and 8,c are afterall in favour of the non-compacted aggregates, the yield response to the effect of compaction on soil water mentioned in 8,a must be considered as minimal.

e) It would have been possible to make an extended statistical analysis of the results, treating each sampling separately. Although this would have provided a better basis for discussion, it would have been very time consuming, and in consultation with the statistician, it was decided that the standard approach, eventually used, caused no appreciable loss of precision in the overall interpretation of the results.

8. Because of the limited time available for this work no field experiment was carried out to test the applicability of the findings of the pot experiments under field conditions. Yet two conclusions could be made:

a) As indicated by the compaction achieved in relation to the past history of the three soils, land use system plays a big role in determining the degree of compaction.

b) Once a soil of a high structural stability is over-compacted, cultivation practices do not improve the micro-structure of the soil.

9. Inasmuch as soil-water status is concerned, if over-compaction is avoided, a degree of compaction could have beneficial consequences especially in areas where drought is a problem.

10. In areas where drought is not a serious problem, it is likely that levels of compaction regarded to give appreciable increases in the AWC of the soil will be accompanied by adverse effects on impedance, soil air, nutrient availability and thermal properties of the soil which could in some situations outweigh the benefits on the soil-water status.

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